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THE GREAT FAULT TROUGHS OF THE ANTILLES[1]

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INTRODUCTION

The region of the Greater Antilles is characterized by a marked elongation of the principal geographic features in an east-west direction and by extremely high relief (Plate I). The highest point above sea-level, Mount Tina on the island of Haiti, has an elevation of over 3,100 m. while the deepest sounding in the Atlantic Ocean (8,526 m.) was obtained only 320 km. to the northeast.[2] The Antillean mountain ranges are among the most precipitous in the world, but their slopes are, in large part, submerged beneath the surface of the Atlantic Ocean and Caribbean Sea. Off the north coast of St. Croix the descent is 4,348 m. in a distance of 8 km., and for shorter distances the slopes are very much steeper.

The physiography of the Greater Antilles is very complex and as yet little of the region has been studied in detail. The dominant tectonic trend is approximately east and west along arcs convex toward the north, in part following the margins of the great trough-like depressions which are such a striking characteristic of the

[1] Presented in part at the Chicago meeting of the Geological Society of America, December, 1920.

[2] All elevations and soundings have been taken from the maps of the Hydrographic Office of the United States Navy.

region. These arcs cut directly across the earlier tectonic lines and are everywhere marked by extremely precipitous slopes.

The evidence outlined in the following pages indicates (1) that the east-west arcs delineating the major relief features of the Greater Antilles are zones of normal faulting developed in late geologic time; (2) that this faulting has resulted in the formation of the great troughs of the region; and (3) that the displacements are continuing at the present time.

CRITERIA OF FAULTING

The fault-zone hypothesis rests partly on geologic evidence, but largely, since most of the region is under water, on evidence that is either topographic or seismologic. Topographic evidence of faulting is unusually well preserved because the fault scarps are mostly below sea-level where they have been protected from erosion. The characteristics of these scarps which indicate an origin through faulting are (1) great height; (2) extremely precipitous slopes; (3) abrupt changes in slope at top and bottom; (4) rectilinear course for long distances; and (5) subordinate depressions and elevations (troughs and horsts) near the base of the main scarps.

The last-mentioned features develop within fault zones as a result of the differential displacement of long narrow blocks or wedges formed by the branching and intersection of nearly parallel faults. The formation of these subordinate troughs and horsts is a common accompaniment of normal faulting on a large scale and especially of trough faulting. On land these minor topographic effects of faulting are soon obliterated by erosion and by the accumulation of rock-waste in the troughs; therefore the significance of these criteria in the recognition and interpretation of faulting has been generally overlooked. Because of their short life these topographic features are seldom found on land except in arid regions and where very recent displacements have occurred along old fault zones. Beautiful examples of this type of fault topography on a small scale have developed along the Wasatch fault zone in Utah as a result of post-Pleistocene displacements. Similar topographic effects were produced in California by the faulting that accompanied

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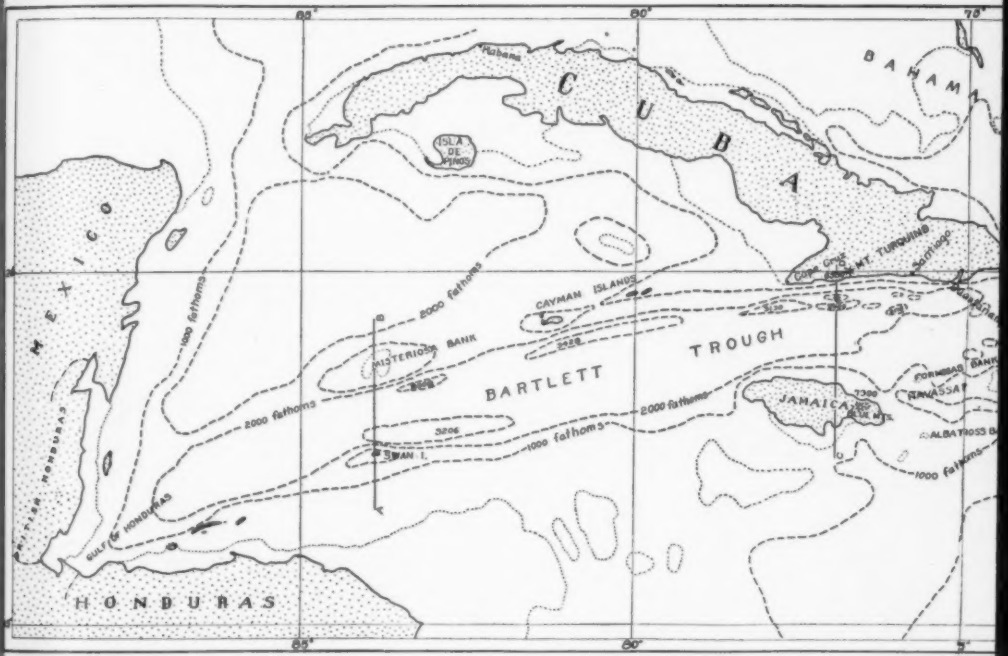
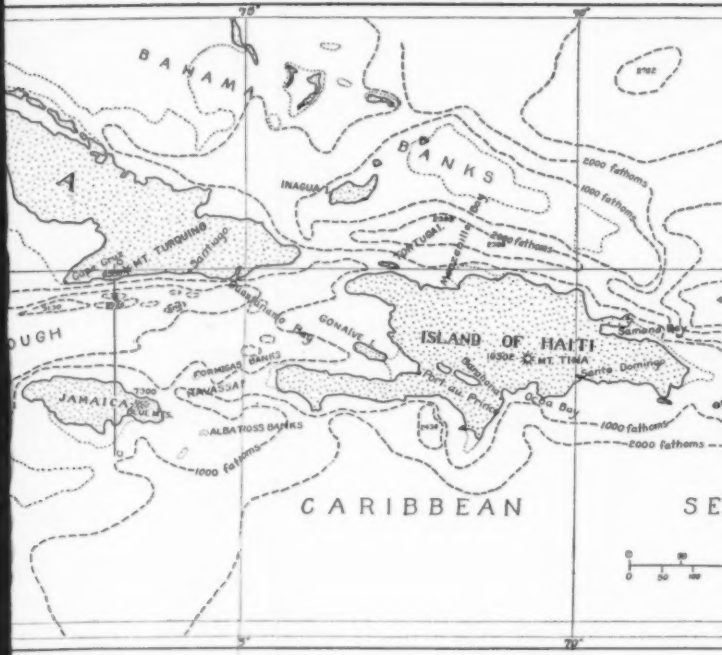


MAP OF THE GREATER ANTLLES

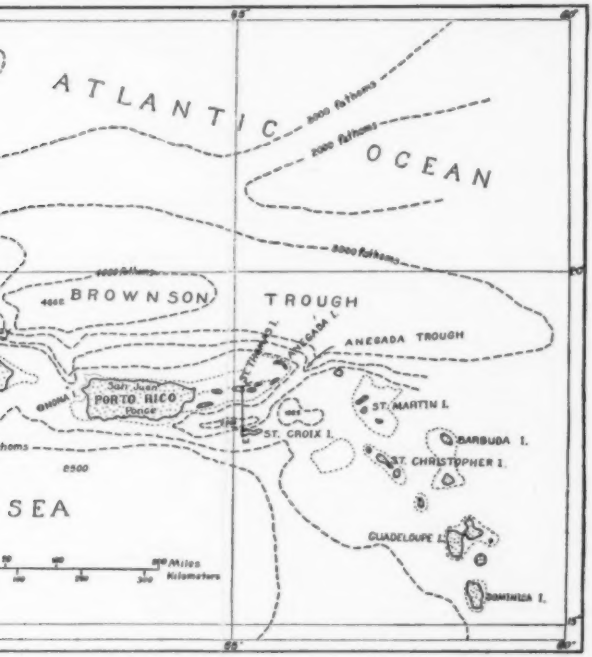
Contour interval, 1,000 fathoms (6,000 feet). Area



MAP OF THE GREATER ANTILLES, SHOWING FAULT TROUGHS

1,000 fathoms (6,000 feet). Areas within the dotted lines, less than 100 fathoms.

PLATE I


ATLANTIC OCEAN
2000 fathoms
2000 fathoms
3000 fathoms
4000 fathoms
4662
BROWNSON
TROUGH
ANEGADA TROUGH
ANEGADA I.
VIRGIN IS.
San Juan
PORTO RICO
Ponce
ST. MARTIN I.
ST. CROIX I.
BARBUDA I.
ST. CHRISTOPHER I.
GUADELOUPE I.
DOMINICA I.
2500
SEA
Miles
Kilometers

the Owens Valley earthquake of 1872;[1] and there are many examples along the line of the San Andreas fault zone of California.

Seismologic evidence, when available, is especially valuable in locating active faults which are not exposed to direct observation. Many earthquakes have been recorded in the Greater Antilles and Virgin Islands during the last four centuries, and, while the published catalogues of these earthquakes are far from complete, it seems probable that few, if any, of the very destructive shocks have been omitted. Most of the weak shocks of a district originate in the same localities as the stronger ones, and therefore in this investigation attention has been focused on the destructive earthquakes. In the region of the Greater Antilles the epicenters of destructive earthquakes, instead of being scattered at random, are almost entirely limited to a few well-defined belts, which also possess the topographic characteristics of fault zones.

Most of the earthquakes occurred before seismographs were developed, and, therefore, in determining the location of their epicenters, it has been necessary to rely chiefly on the distribution of intensities and the evidence derived from a study of accompanying sea waves. Fortunately, for present purposes an approximate location of an epicenter is, in most cases, sufficient. The seismologic data are only briefly summarized here as they are discussed in more detail in another paper which will be published shortly in the *Bulletin of the Seismological Society of America*.

DESCRIPTION OF FAULT ZONES AND FAULT TROUGHS

The principal troughs of the Antillean region are: the Bartlett Trough, which lies between Cuba and Jamaica and extends from the Island of Haiti westward into the Gulf of Honduras; the Brownson Trough, lying immediately north of Porto Rico and the Virgin Islands; and the Anegada Trough, which separates Porto Rico and the Virgin Islands Bank from St. Croix and the Lesser Antilles. In addition to these there are some minor troughs and probably one fault zone that is not associated with any trough.

[1] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Surv. Monograph I* (1890), p. 361.

THE BARTLETT TROUGH[1]

The Bartlett Trough is probably the most striking physiographic feature of the Antillean region (Fig. 1). It is a long, narrow trench stretching from the Gulf of Honduras eastward into Gonaïve Gulf between the two western peninsulas of Haiti, a distance of 15° or 1,570 km. Its width, where widest, between Cuba and Jamaica and near the Cayman Islands is 150 to 160 km. Its deepest sounding, 3,506 fathoms (6,412 m.) was obtained less than 50 km. from the coast of Cuba and is over 8,275 m. below the higher peaks of the Blue Mountains in Jamaica and the Sierra Maestra in southern Cuba. The six deepest places (all over 3,000 fathoms) are close to the inclosing scarps rather than near the center of the trough. The floor of the trough seems to be relatively flat over quite large areas, but in longitudinal profile rises and falls throughout its length. The Bartlett Trough lies between two great fault zones which may be traced longitudinally far beyond the limits of the trough itself. They are here designated the Swan Island–Jamaica–South Haiti fault zone and the Cayman Islands–Sierra Maestra–North Haiti fault zone.

Swan Island–Jamaica–South Haiti Fault Zone.—This fault zone may be traced westward from its juncture with the northern escarpment of the Caribbean Basin in the vicinity of Ocoa Bay, Santo Domingo, across Haiti, and along the southern side of the great Bartlett Trough. On the Island of Haiti it is marked by a trough-shaped valley 15 to 20 km. in width, which extends from Barahona on Neyba Bay to Port-au-Prince, a distance of about 150 km. Throughout its length this depression is confined between the precipitous fronts of two lofty mountain ranges. The floor of the trough comprises the plain of the Cul de Sac in the west, the plains of Neyba in the east, and the lake region lying between. Two of the lakes contain salt water, and W. F. Jones states that they are both below sea-level, but at different elevations.[2] A very slight subsidence of the land would com-

[1] A brief description of this trough was given in a previous paper, "Jamaica Earthquakes and the Bartlett Trough," *Bull. Seis. Soc. of Amer.*, Vol. X (1920), pp. 84–88.

[2] W. F. Jones, "A Geological Reconnaissance in Haiti, A Contribution to Antillean Geology," *Jour. Geol.*, Vol. XXVI (1918), p. 730.

pletely submerge the floor of the trough and separate the Tiburon Peninsula from the rest of Haiti.

The depression has been described and figured by Jones as a normally faulted block, buried under Quaternary deposits which have been removed at one place exposing highly tilted Oligocene-Miocene sediments. Limestones of Eocene–Early Oliogcene age are exposed along the flanks of the inclosing ranges while late Tertiary intrusives form the core of the mountains on the south. Another "large fault is indicated well up on the south range of Haiti, a well-marked depression extending east and west along the course of this fault."[1]

Along the north side of the salt lakes Jones found basalt-flows, which he thinks came from fissure eruptions; and he states that between the Cul-de-Sac depression and Ville Bonheur (Saut d' Eau) there is a well-defined crater from which extend basalt-flows, so recent in origin that they have not been appreciably modified by erosion.[2] In the Province of Azua, Santo Domingo, there are rocks of igneous origin, which C. W. Cooke states are not older than Pleistocene.[3]

During historic times the fault trough of southern Haiti has been the locus of more earthquakes of high intensity than any similar area in the Greater Antilles. The high seismicity of this depression is noted by Scherer in his excellent article on "Great Earthquakes in the Island of Haiti"[4] from which most of the data on Haitian earthquakes given in this paper have been abstracted.

The cities of Azua and Santo Domingo, located on alluvial ground a short distance north of the fault zone and near its juncture with the Caribbean escarpment, have been damaged repeatedly by earthquakes. They suffered from severe shocks in 1673, 1684, and 1691, Azua being entirely destroyed in 1691. On October 18, 1751, an earthquake threw down all houses in Azua and a sea-wave overwhelmed the town. It was rebuilt farther inland.

[1] *Ibid.*, p. 751. [2] *Ibid.*, pp. 750–51.

[3] C. W. Cooke, "Geological Reconnaissance in Santo Domingo," *Bull. Geol. Soc. Amer.*, Vol. XXXI (1920), p. 218.

[4] Rev. J. Scherer, "Great Earthquakes in the Island of Haiti," *Bull. Seis. Soc. Amer.*, Vol. II (1912), pp. 161–80.

Other towns near the coast were severely damaged, Santo Domingo City losing many of its finest buildings. The earthquake of 1751 and several other shocks, assigned by Scherer to the central valley of Haiti, are here correlated with the southern fault trough because of high intensities near the coast and the phenomena of the sea-wave. The earthquake of May 11, 1910, cracked walls in Azua and Santo Domingo City. Scherer states that "the strongest part of the earthquake occurred in the Bay of Ocoa where the sea-wall was broken."[1]

The fault trough apparently continues westward into the Gulf of Gonaïve, for there is a marked depression between Gonaïve Island and the straight north coast of the Tiburon Peninsula. The earthquake of November 9, 1701, threw down masonry houses on the plains near the western end of the trough, and the road along the north shore of the Tiburon Peninsula from Léogâne to Petit Goâve sank into the sea. The severe earthquakes of November 21 and 22, 1751, destroyed the recently founded town of Port-au-Prince and overthrew buildings on the plain of the Cul de Sac. Lyell states that "part of the coast 20 leagues in length sank down and has ever since formed a bay of the sea,"[2] but the writer has found nothing which would confirm this assertion.

The earthquake of June 3, 1770, was one of the strongest shocks recorded on the Island of Haiti, the area of greatest destruction extending from Croix de Boquets through the plain of the Cul de Sac to Port-au-Prince and along the north coast of the Tiburon Peninsula as far as Miragoâne. Southey states that "the sea rose a league and a half up into the island"[3] but does not mention where this occurred. Scherer states that at Grand Goâve the foot of the mountain of La Saline was partly submerged and at Arcahaie north of Port-au-Prince, a wave was also recorded.[4]

The earthquake on the night of April 8, 1860, originated a little farther west than the disturbances previously described, the inten-

[1] Rev. J. Scherer, *op. cit.*, p. 172.

[2] Sir Charles Lyell, *Principles of Geology*, Vol. I, p. 440, London, 1830.

[3] Thomas Southey, *Chronological History of the West Indies*, Vol. II, p. 407, London, 1827.

[4] Rev. J. Scherer, *op. cit.*, p. 178.

sity being greatest from Petit Goâve to Anse à Veau, but towns as far east as Port-au-Prince had houses thrown down or badly damaged. In the vicinity of Anse à Veau the sea withdrew and then broke with a crash on the shore.

Soundings indicate that the fault trough of southern Haiti continues westward as a topographic feature at least as far as the end of the Tiburon Peninsula; and, while it cannot be traced farther, the trend of the entire depression is in alignment with the southern scarp of the Bartlett Trough north of Jamaica. Evidence that the north coast of Jamaica is determined by a fault zone has been given elsewhere.[1] Briefly summarized, it is as follows:

1. The coast is an almost straight line from Port Maria to Montego Bay, a distance of nearly 113 km., where it is offset about 8 km. to the south and then continues westward to Pedro Point. The east-west line between Pedro Point and Montego Bay is continued eastward by the valley of Montego River which runs parallel to the coast for 16 km.

2. The land rises steeply from the sea to the plateau surface which has an elevation of 300 to 400 m. Wave erosion could not have produced these bluffs in the relatively short time that it has been active, and there is no broad, wave-cut terrace either above or below sea-level. The steep slopes continue below the sea and depths of 1,000 to 2,251 fathoms (1,829 to 4,117 m.) are attained within less than 15 km. of the shore.

3. There is a sudden change in slope both at the top and bottom of the escarpment.

4. The Tertiary beds terminate abruptly along the coast and in places the uplift has exposed the older underlying rocks.

5. The occurrence in modern times of several severe earthquakes with their epicenters a short distance off the coast indicates that there is here a zone of instability along which adjustments are still going on. The earthquake of 1692—one of the great catastrophes of history—and the destructive earthquake of 1907 both originated off the north coast of Jamaica and both were accompanied by sea-waves.

[1] Stephen Taber, "Jamaica Earthquakes and the Bartlett Trough," *Bull. Seis. Soc. Amer.*, Vol. X (1920), pp. 55–89.

Passing westward from Jamaica, soundings show that the steep southern escarpment of the Bartlett Trough continues toward Swan Island, and everywhere with abrupt changes in slope at top and bottom. Swan Island has the topographic characteristics of a horst which has remained standing within the zone of subsidence (see Fig. 1).

Great Swan Island is only 2.5 km. in length and about 20 m. in height; Little Swan Island is scarcely more than a reef. The submarine slopes in the vicinity of the islands are precipitous: on the south a sounding of 1,053 fathoms (1,926 m.) was obtained

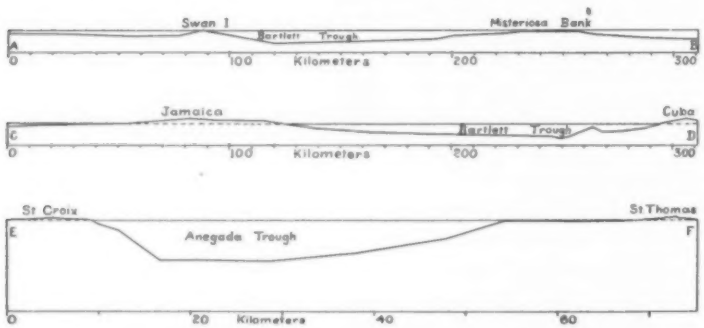


FIG. 1.—Profiles of the Bartlett and Anegada Troughs. Vertical and horizontal scales the same. Additional soundings would show the scarps to have steeper rather than gentler slopes.

within 10 km., the descent continuing until a depth of 2,136 m. is reached 16 km. from the island, after which the sea-bottom rises rapidly to the edge of the submerged Honduras-Jamaica Plateau; toward the north, a depth of 3,010 fathoms (5,505 m.) is attained within 32 km. of the island, thus giving an average slope of about one in six.

The latter sounding was obtained in a long, narrow depression lying at the foot of the scarp. The 3,000-fathom contour surrounding the depression (see map, Plate I) extends eastward from Swan Island along the base of the scarp for 200 km. or more. It has an average depth, below the floor of the Bartlett Trough in this vicinity, of over 1,000 m., the deepest sounding recorded being

3,206 fathoms (5,858 m.). The general form of this depression, in so far as it has been revealed by soundings, and its alignment with the fault trough of southern Haiti, together with the presence of other depressions of unknown shape nearer Jamaica, suggest that there has been more or less trough faulting all along the arc from Ocoa Bay to Swan Island.

Swan Island is built of limestone, mostly Pleistocene or Recent in age. A specimen from the higher part of the island consists chiefly of the coral, *Orbicella cavernosa* (Linn.). The particular form present in the specimen now lives in those waters and has not been found in deposits older than Pleistocene. In places the rock is a loosely cemented, coarse, calcareous sandstone. Pebbles and bowlders of hard limestone, containing terrigenous material, are abundant along the beaches. A specimen, showing well-defined, closely spaced bedding-planes and made up largely of *Globigerina* with amorphous silica filling the cavities, contained flakes of muscovite one millimeter in diameter and subangular quartz grains. Another specimen stained with ferric oxide, contained about 1.5 per cent Al_2O_3 as well as some quartz.[1] The land mass from which these terrigenous materials were derived must have been close at hand, but it has entirely disappeared.

It has not been possible to obtain seismologic data for Swan Island extending back over a long period of time, but during the summer of 1920 two shocks were felt.[2] On July 11 at 10:40 A.M. a distinct rumbling was heard, and this was immediately followed by a pronounced shock, apparently vertical, lasting five seconds. On August 18 at 6:04 P.M. a rather violent earthquake of approximately fifteen seconds' duration was experienced. The motion was reported as vertical and similar in character to that of the earthquake of July 11. No unusual sea conditions were noticed. Tools were dislodged in the engine-room and shop of the

[1] A set of rock specimens was procured from Swan Island through the courtesy of George S. Davis, General Manager of the Radio Telegraph Department of the United Fruit Company. The writer is also indebted to him for his kindness in furnishing seismologic data for Swan Island. The specimen of coral was identified by Dr. T. W. Vaughan, and the *Globigerina* by Dr. Jos. A. Cushman and Dr. Vaughan.

[2] These earthquakes were observed and reported by George H. Rogers, Chief Operator of the Swan Island Radio Station.

Radio Station, some falling from racks to the floor, but no damage resulted. The descriptions of these two earthquakes and the fact that they were not recorded on the seisomographs at Panama, Port-au-Prince, or Vieques indicate that they were local, probably originating close to Swan Island.

An earthquake at $11^h\ 01^m\ 46^s$ G.M.T. on January 1, 1910, was of sufficient intensity to throw two men out of bed. Instrumental records indicate an origin about 35 miles south of Swan Island but this determination is not regarded as very accurate.[1]

The submerged scarp bounding the Bartlett Trough on the south continues beyond Swan Island in a southwesterly direction and is especially well defined north of the Bay Islands (Utilla, Ruatan, and Bonacca) where it has a height of about 4,000 m. The Bay Islands are probably the eastern continuation of the Sierra de Omoa of Honduras[2] and they are also in alignment with Swan Island. Basalt-flows on the Island of Utilla and in the Sierra de Omoa at Chameleconcito near Puerto Cortez are believed by Powers to be Recent, perhaps Pleistocene in age;[3] and their presence is indicative of profound faulting such as has permitted the effusion of basalts in the fault trough of Southern Haiti.

Topographic evidence suggests that the separation of Jamaica and Haiti has resulted from faulting along a branch of the Swan Island–Jamaica–South Haiti fault zone, extending from a point near the north coast of Jamaica eastward along the south coast of Haiti until it joins the northern escarpment of the Caribbean Basin. The Tiburon Peninsula of Haiti continues westward beyond Cape Dame Marie as a submarine ridge for 150 km., passing through Navassa Island and Formigas Bank; a parallel ridge extends eastward from Morant Point, Jamaica, through Albatross Bank for a distance of over 100 km.; between the two lies a narrow channel having a nearly uniform depth of 2,000 m. Immediately south of the Tiburon Peninsula there are very steep slopes, especially near Vache Island and near Jacmel where soundings of over

[1] These data were supplied by Professor Harry Fielding Reid.

[2] Karl Sapper, "Über Gebirgsbau und Boden des südlichen Mittelamerika," *Petermann's Mitteil.*, Bd. 32, Heft 151 (1906), p. 17.

[3] Sidney Powers, "Notes on the Geology of Eastern Guatemala and Northwestern Honduras," *Jour. Geol.*, Vol. XXVI (1918), p. 514.

3,932 m. have been obtained within 20 km. of the coast. There is no evidence of important seismic activity along this branch zone east of Jamaica, and therefore, if the channel be due to faulting, as seems probably, a condition of at least temporary stability has been attained.

The Cayman Islands–Sierra Maestra–North Haiti Fault Zone.—This fault zone extends along the north side of the Bartlett Trough, crosses the Island of Haiti between Manzanillo Bay and Samana Bay, and, in the vicinity of Mona Passage, joins the fault zone which forms the south side of the Brownson Trough.

The Sierra Maestra range, after closely following the straight east-west coast of southern Cuba, continues westward as a submarine ridge, which, bearing slightly toward the south, reappears above the surface in the Cayman Islands and almost reaches the surface in the Misteriosa Bank. It culminates in the Pico del Turquino which rises abruptly from the sea to an altitude of 2,000 m. The precipitous southern slope of the range is continued below sea-level to depths of over 6,000 m., forming one of the most magnificent fault scarps known. At the base of this scarp, which forms the north side of the great Bartlett Trough, there is a narrow subordinate trough or series of elongated depressions containing four of the deepest soundings obtained in these waters; and it is interesting to note that these soundings are located opposite points where the top of the scarp is relatively high. The four soundings are: 5,501 m. immediately southeast of Misteriosa Bank; 6,269 m., 32 km. south of the Cayman Islands; 5,724 m., 35 km. south of Cape Cruz; and 6,412 m., 50 km. south of Turquina Peak. In passing south from Turquina Peak there is a precipitous descent to something more than 2,286 m. below sea-level, and then an ascent to 1,582 m. below sea-level before the descent to 6,412 m. is made (see profile, Fig. 1). Farther east there are other submerged peaks or ridges near the base of the scarp.

Vaughan has referred to the precipitous profiles along the south shore of Cuba as indicative of faulting and states that this interpretation is supported by the geologic structure.[1] The La Cruz marl

[1] T. W. Vaughan, "Some Littoral and Sublittoral Physiographic Features of the Virgin and Northern Leeward Islands and Their Bearing on the Coral Reef Problem," *Jour. Wash. Acad. Sci.*, Vol. VI (1916), p. 56.

(Miocene) is abruptly cut off by faulting at the shore line near the mouth of Santiago Harbor.[1]

Seismologic data are not available for the Cayman Islands, and because of sparse population little is known about the effects of earthquakes along the Sierra Maestra scarp except at Santiago de Cuba. This city, founded in 1514, has been repeatedly damaged by earthquakes.[2] Strong earthquakes were recorded at Santiago in 1578, 1675, and 1677. Kimball states that the city was destroyed by the shock of 1675,[3] but the writer has not been able to verify this statement. The earthquake of February 11, 1678, known in Cuban tradition as the *great earthquake*, caused enormous destruction in Santiago; and exactly one year later the cathedral was destroyed by another shock. The severe earthquake of 1755 was accompanied by a sea-wave which almost completely inundated the town. The strongest earthquake recorded at Santiago, according to Salterain, occurred June 11, 1766, and it was followed by a large number of aftershocks. Many buildings were completely destroyed and others were badly damaged. Between 1777 and 1852 eighteen important earthquakes are listed by Salterain, the earthquake of August 20, 1852, and its aftershocks being especially severe.

In contrast with the Sierra Maestra region the north and central parts of Cuba have been virtually free from seismic disturbances. A severe earthquake followed by aftershocks originated in the Sierra de los Organos of western Cuba in 1880, but, before that time and since, earthquakes have been almost unknown in that section.

Passing eastward from the Bartlett Trough the fault zone is marked by a depression which obliquely crosses the Windward Passage and extends between Tortuga Island and the coast of Haiti. The depression enters Haiti through Manzanillo Bay, and,

[1] T. W. Vaughan, "Geological History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 626.

[2] Most of the facts concerning Cuban earthquakes given in this paper have been abstracted from "Ligera Reseña de los Temblores de Tierra Occuridos en la Isla de Cuba" by P. Salterain, *Boletin de la Comisión del Mapa Geólogico de España*, Vol. X, pp. 371–85, Madrid, 1883.

[3] R. B. Kimball, *Cuba and the Cubans*, p. 20, New York, 1850.

as a land valley, crosses the island to Samana Bay, a distance of 240 km. This great valley was named the Véga Real by Columbus in 1494, but now the name is usually limited to the eastern portion. It is very similar topographically to the great valley of southern Haiti. The floor of the valley, less than 25 km. in width, consists of a series of broad plains lying between the Sierra de Monte Christi on the north and the Grande Hilera on the south. The valley is drained by two rivers, the Yaqui del Norte and the Yuma, flowing in opposite directions.

The geologic structure of the valley has not been studied in detail. Cooke,[1] who has recently visited the region, states that the south front of the Cordillera Sententrional (Sierra de Monte Christi) is a fault scarp which brings up Eocene and Cretaceous rocks high above upper Miocene. The displacement is therefore in the same direction as along the Sierra Maestra fault. Cooke found several faults of slight displacement along the Gurabo River near the southern side of the Véga Real and states that these are probably normal, with uplift on the north. There are other faults of much greater magnitude near the southern side of the Véga Real and in the adjacent part of the Cordillera Central, but no data are now available concerning them. Cooke believes that faulting has been an important factor in shaping some of the boundaries of the Véga Real, but he does not regard the valley as a simple down-dropped fault block.

The high seismicity of the great northern valley of Haiti was recognized by Scherer, who states that the first great earthquake mentioned in histories of Haiti occurred here in 1564. It resulted in the destruction of Conception de la Véga and Santiago de los Caballeros, two cities in the Véga Real about 30 km. apart. In 1783 the principal church at Santiago was partly thrown down by an earthquake and several buildings were destroyed.

The earthquake of May 7, . 42, was one of the most severe recorded on the island. Destruction was greatest at Cap Haitien, a city of ten thousand inhabitants, which lost half of its population. The intensity was almost equally as high at Môle St. Nicolas,

[1] Dr. C. W. Cooke kindly furnished information concerning the geologic structure of the Véga Real in letters dated January 26, and October 5, 1920.

Port de Paix, Fort Liberté and Santiago de los Caballeros, all of which were destroyed with the loss of several thousands of lives. At Cap Haitien waves dashed against buildings along the quay; at Port de Paix the sea withdrew 60 m. and, upon returning, buried the city under 4 or 5 m. of water. The bed of the Yaqui River is said to have been suddenly elevated, driving its waters both up and down stream. The shock was severe at Santiago de Cuba and was felt throughout the length of the Sierra Maestra. The distribution of intensities and the phenomena of the sea-wave indicate that the earthquake was caused by a vertical displacement along a fault passing between Tortuga Island and St. Nicholas Peninsula.

The earthquake of December 29, 1897, seems to have originated in the central part of the Yaqui Valley, the intensity being greatest between Guyaubin and Santiago and at Altamira. At Guyaubin and Santiago great cracks were formed and subsidence of the ground was reported.

Scherer correlates the disastrous earthquake of September 23, 1887, with the great northern valley, but the writer thinks that it was caused by a vertical displacement along a fault near the east end of the Bartlett Trough, a short distance south or southwest of Môle St. Nicolas. The destruction was greatest at Môle St. Nicolas, nearly all of the houses being thrown down. Buildings were also damaged or destroyed at Cap Haitien, Port de Paix, Gonaïves, and other places. A sea-wave followed the earthquake and was reported from points along the shores of Gonaïve Gulf as far as Anse d'Hainault on the end of the Tiburon Peninsula; at Jérémie on the north coast of the Tiburon Peninsula the sea withdrew 20 m. and returned with a rush. Along the north coast of the St. Nicholas Peninsula, however, the wave seems to have been of no importance. The shape of the St. Nicholas Peninsula suggests that both its north and its south coasts may have been determined by faulting.

Three other Haitian earthquakes of moderately high intensity cannot be correlated with either of the great fault valleys. One originated in the eastern part of the island in 1882 and damaged the churches at Seybo and Higuey; another, which occurred October 6, 1911, was of highest intensity in the central part of the

island and probably originated on the south flank of the Grande Hilera or in the central valley of Haiti. This valley, according to Jones, was formed by folding and erosion rather than by faulting.[1] The earthquake of April 23, 1916, which damaged buildings at Boya, Guerra, and Bayaguana, seems to have originated near latitude 18° 45′ N., longitude 69° 45′ W.

The separation of Cuba and Haiti has been attributed by Vaughan to the downthrow of a block between two faults; one forming the north side of the Bartlett Deep, the other forming the south side and converging toward the former in the Windward Passage.[2] The evidence summarized in the present paper indicates that the separation of the two islands is to be correlated with the formation of the series of depressions, including the Véga Real, which mark the Cayman Islands–Sierra Maestra–North Haiti fault zone, and which have probably originated through differential displacement of relatively narrow blocks or wedges within that zone.

A narrow trough, 3,058 to 4,353 m. in depth, separates the Island of Haiti from the Bahama Banks. It extends eastward, in a great arc convex toward the north, from a point north of the Windward Passage and enters the Brownson Trough northeast of the Samana Peninsula. The topographic characteristics of this trough and its parallelism to the two Bartlett Trough fault zones suggest that it has originated through faulting; but no geologic evidence of faulting is known and little seismologic evidence is available except for the extreme eastern end where it joins the Brownson Deep (see page 106).

THE BROWNSON TROUGH

The Brownson Trough, containing the deepest sounding made in the Atlantic Ocean, parallels the Porto Rico–Virgin Islands ridge on the north. Its shape is not known in detail for as yet few soundings have been made in these waters. The 4,000-fathom contour surrounds a narrow area, about 320 km. long in an east-west direction; and the 3,000-fathom contour which is approxi-

[1] W. F. Jones, *op. cit.*, *Jour. Geol.*, Vol. XXVI (1918), pp. 735–36 and Plate V.

[2] T. W. Vaughan, "Geologic History of Central America and the West Indies During Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), pp. 625–26.

mately concentric extends nearly three times as far. The trough is deepest near its western end.

On the south the trough is bounded by a great scarp that rises steeply to the plateau-like ridge on which Porto Rico and the Virgin Islands stand, the average slope being about one in thirteen. The rectilinear north coast of Porto Rico and the steep submarine scarp descending from it are indicative of faulting. This coast is bordered, near the west end of the island, by a long line of high cliffs which evidently represent a fault scarp, for the youthful topography of the plateau back of the cliffs and the gorge-like valley of Guajataca River near its mouth testify to a recent elevation of the land, whereas a long period of time would be required for the sea to cut such cliffs in gently dipping rock strata. A wave-cut bench at the foot of the cliffs marks the latest uplift of the land, amounting to several meters; and a similar sea-terrace bordering Desecheo Island proves that this recent elevation extended at least that far westward.[1] The abrupt change in the slope near the 100-fathom contour about 8 km. north of the sea-cliffs and the occurrence of earthquakes at points lower down along the slope indicate the presence of a zone of faulting, and suggest that the descent into the trough is not accomplished by a single fault scarp.

The fault zone along the south side of the Brownson Trough is possibly the eastward extension of the Cayman Islands–Sierra Maestra–North Haiti fault zone, but if so, there is a sharp flexure in the trend of the zone immediately north of Mona Passage, and the downthrow changes to the opposite side. The topography of this critical region, in so far as it has been revealed by soundings, suggests that the ends of the two zones overlap and intersect; and this may explain the origin of the peculiar submarine valley, which, heading in Aguadilla Bay, extends northwestward into the Brownson Trough. This valley was described and figured in a previous paper.[2] At Aguadilla the coast has been slowly sinking during the last half-century, while at Mayagüez, 23 km. farther south as well

[1] Harry Fielding Reid and Stephen Taber, "The Porto Rico Earthquakes of October–November, 1918," *Bull. Seis. Soc. Amer.*, Vol. IX (1919), p. 120.

[2] *Ibid.*, pp. 118–21 and Plates 13 and 14.

as along the north coast the land has been rising. The seismicity of the region immediately north of Mona Passage is high.

Many earthquakes have been recorded in Porto Rico and the Virgin Islands.[1] Most of them have had a low intensity and have been reported from only one or two places, so that it is impossible to determine accurately their epicenters, but it is usually possible to locate, approximately at least, the epicenters of the stronger shocks. If consideration is limited to earthquakes which have had a probable maximum epicentral intensity of above VI in the Rossi-Forel scale, it is found that, with very few exceptions, they have originated along the steep slopes descending into the Brownson or the Anegada troughs.

The earthquake of April 16, 1844, which damaged buildings at Isabela on the north coast of Porto Rico, probably had its origin a short distance north or possibly northwest of the island. The shock of November 28, 1846, was most strongly felt in the northwestern part of Porto Rico where some buildings were injured, the distribution of the intensity indicating an origin off the northwest coast. The earthquake of October 11, 1915, which was felt over most of Porto Rico and as far west as Puerto Plata, Santo Domingo, probably originated a short distance north of Mona Passage.

The destructive earthquake of October 11, 1918, with its accompanying sea-wave, and the strong aftershocks of October 18 and 24 and November 12, as well as a host of weaker shocks felt during 1918–19, all originated a few kilometers west of Point Borinquen on the northwest coast of Porto Rico.

Other earthquakes have originated at points farther east along the southern scarp of the Brownson Trough. On the night of December 8, 1875, an earthquake, which probably had its epicenter a short distance north of the coast, damaged buildings in Arecibo. The earthquake of September 27, 1906, having an epicentral

[1] A catalogue of earthquakes felt in Porto Rico and the Virgin Islands from 1772 to 1918 was given in "The Porto Rico Earthquake of 1918 with Descriptions of Earlier Earthquakes. Report of the Earthquake Investigation Commission," by Harry Fielding Reid and Stephen Taber, *Document No. 269*, U.S. House of Representatives, 66th Congress, 1st Sess. (1919), pp. 53–66.

intensity close to IX R.-F., originated about 50 km. north of the coast and opposite the middle of the island; and the shock on September 5, 1908, with slightly lower intensity seems to have had its origin in approximately the same locality. On July 7, 1869, two light shocks were felt on board the ship *Esther and Sophie* when about 20 km. north of Culebra Island. The earthquake of February 17, 1909, felt over the greater part of Porto Rico and the Virgin Islands, originated along the steep submarine slopes north of Culebra and St. Thomas. On October 29, 1886, an earthquake was felt on board the British brigantine *Wilhelmina* while over the steep scarp 75 km. north of Anegada Island.

The north side of the Brownson Trough is entirely under water few soundings have been made in its vicinity, and it is so far from the land that earthquakes originating along its slopes could cause little or no damage; therefore evidence of faulting is not abundant. A broad ridge rising 3,200 to 5,600 m. above the floor of the trough separates it from the North Atlantic Basin. The trough-like depression separating Haiti from the Bahama Banks apparently joins the north slope of the Brownson Trough at a slight angle, in much the same way that the Cayman Islands–Sierra Maestra–North Haiti fault zone joins the fault zone on the south side of the Brownson Trough.

On February 19, 1883, the bark *Siddartha* experienced a sharp earthquake, lasting 25 seconds, while over the north side of the Brownson Trough in lat. 20° 04′ N., long. 67° 41′ W. The bark trembled as if dragging over a hard bottom although the depth here is more than 6,000 m.

On November 29, 1916, and on July 13 and 26, 1917, severe earthquakes originated in the vicinity of lat. 19° 30′ N., long. 68° 30′ W. The last of these shocks was felt over most of Haiti and Porto Rico and probably had an intensity of IX R.-F. near the epicenter. It was followed by a series of aftershocks lasting several days. These earthquakes of 1916 and 1917 should be correlated, perhaps, with the trough that separates Haiti from the Bahama Banks for they originated in the area where it joins the Brownson Trough (see page 103).

THE ANEGADA TROUGH

The Anegada Trough, separating Porto Rico and the Virgin Islands group from St. Croix and the Lesser Antilles is the deepest of the many passages connecting the Caribbean Sea with the Atlantic Ocean. A description of this trough accompanied by a map and transverse profile was given in a previous paper.[1]

It is deepest midway between St. Croix and Vieques where a sounding of 2,501 fathoms (4,574 m.) was obtained; here it extends nearly east and west for 100 km. Between St. Croix and the islands of St. Thomas and St. John the depth is over 2,000 fathoms. Farther east the trough rises until the depth is a little over 1,000 fathoms and there it bifurcates. One branch seems to extend northeast and join the Brownson Trough about 60 km. northeast of Anegada Island, where the depth is over 3,000 fathoms; the other extends eastward in the direction of St. Martin but is not well defined. In its deeper parts the trough is about 40 km. in width between the tops of the inclosing scarps, which show abrupt changes in slope at both top and bottom. The floor of the trough is relatively flat.

The south side of the trough near St. Croix and westward therefrom is bounded by a tremendous fault scarp (see profile Fig. 1). Near Harms Bluff at the northwest corner of St. Croix the scarp descends 4,348 m. in 8 km., an average slope of 30°. For a distance of 4.4 km. the slope averages over 37°, and for shorter distances it is much steeper. Vaughan states that the faulting has taken place so recently that the sea has barely cut a niche into the fault plain.[2] The northern scarp of the trough does not touch the coast of any of the islands; it lies 15 km. south of St. Thomas and 6 or 7 km. from Vieques. It is not so precipitous as the opposing scarp, the average slope being about 12°, though in places it is much steeper.

[1] Harry Fielding Reid, and Stephen Taber, "The Virgin Islands Earthquake of 1867–1868," *Bull. Seis. Soc. Amer.*, Vol. X (1920), pp. 20–25.

[2] T. W. Vaughan, "Some Features of the Virgin Islands of the United States," *Asso. Amer. Geog. Ann.*, Vol. IX (1920), pp. 78–82.

Several severe earthquakes have originated in the Anegada Trough and many light shocks are recorded by the seismographs on the Island of Vieques. A severe earthquake was felt in Antigua, St. Christopher, and Tortola July 11, 1785. Since the shock was strongly felt on all three islands its epicenter was probably between them; and the report that cracks were formed in the ground in Tortola suggests an origin in the vicinity of that island.

A severe shock was felt in St. Thomas, April 20, 1824. The precise location of the epicenter cannot be determined from the data available but is not far from St. Thomas, probably in the Anegada Trough, though possibly on the opposite side of the island along the southern scarp of the Brownson Trough. The strong shock reported from St. Thomas September 19, 1853, and the two felt on May 12, 1865, appear also to have originated near that island.

The great earthquakes of November 18, 1867, originated along the northern scarp of the trough 15 to 20 km. south of St. Thomas. There were two strong shocks separated by an interval of about 10 minutes, both being followed by sea-waves. Aftershocks continued for several months, the strongest occurring December 1 and 12, 1867; January 5 and March 17, 1868, and September 17, 1869. The shock on March 17, 1868, was accompanied by a small sea-wave and seems to have had its epicenter a little farther west than the others, though all originated along the same scarp.

On July 24, 1913, a severe earthquake was felt in the Virgin Islands and throughout Porto Rico except along the west coast. The epicenter was apparently in the Anegada Trough near latitude 18° 30′ N., longitude 64° W.

THE NORTHERN ESCARPMENT OF THE CARIBBEAN BASIN

The Caribbean Basin is bounded on the north by an escarpment that descends steeply from Porto Rico and Haiti to a depth of 4,572 m. within 90 km. of the islands. This is the only important scarp in the region that does not form one side of a relatively narrow trench. It gives the Porto Rico–Virgin Islands ridge, extending eastward from Haiti, the topographic characteristics of a great horst.

Near Ponce on the south coast of Porto Rico, Berkey has traced an east-west fault which he thinks is of very late Tertiary age.[1] It brings the older rocks of the pre-Tertiary into contact with the younger series forming the present coastal margin. This fault may be one of a series by which the descent to the floor of the Caribbean Basin is accomplished. There is, however, no topographic evidence of recent displacements along it; and the Seismic history of the region indicates that, if the Caribbean scarp be due to faulting, it is now relatively stable. The epicenter of no earthquake can be definitely assigned to this scarp, although some of the shocks reported only from the south coasts of Porto Rico and Haiti may have originated there. Certainly no disastrous earthquakes and comparatively few light shocks have occurred there in several centuries.

On August 4 and 13, 1908, moderately strong shocks were felt at Ponce and neighboring points. The intensity was about VI R.-F., and some buildings were slightly damaged. The origin was probably not far from Ponce.

Earthquakes of low intensity have originated at many places in Porto Rico, but in contrast with the north coast none has had an intensity of more than VI or VII. A shock on August 30, 1865, which slightly damaged churches at Manatí and Ponce, probably had its origin near the center of the island. On October 23, 1860, an earthquake with intensity of VI–VII caused some damage at Mayagüez on the west coast, and the epicenter was probably not far away. Several light shocks have originated in the eastern part of Porto Rico near Cidra, the strongest, on October 22, 1901, having an intensity of about VI.

RELATION OF FAULT ZONES TO EARLIER TECTONIC TRENDS

The fault zones described in this paper collectively form a great fault system which extends from the eastern end of the Brownson Trough westward to the Gulf of Honduras, a distance of 2,500 km. The two fault zones inclosing the Bartlett Trough are apparently in alignment with the Matogua Valley and the

[1] C. P. Berkey, "Geological Reconnoissance of Porto Rico," *Ann. N.Y. Acad. Sci.*, Vol. XXVI (1915), p. 40.

Polochie–Lake Izabal Valley in Guatemala, but Powers who has recently visited the region states that he believes these valleys are due to erosion dependent on folding.[1] Sapper,[2] in mapping the tectonic lines of Central America attributes the east-west ranges of Guatemala to folding, and this view has been adopted by other geologists. If the Antillean fault zones continue westward beyond the Gulf of Honduras their curvature is reversed, for in Central America the mountain ranges extend in approximately parallel arcs convex toward the south.

The Central American ranges, as they approach the Gulf of Honduras, curve gradually toward the northeast, and therefore meet at an angle the north coast of Honduras which extends east and west. Powers states that this coast is evidently a fault-zone area.[3] Vaughan correlates the tectonic lines of Honduras with the submarine ridge or plateau connecting the Honduras Peninsula with Jamaica,[4] but this feature is abruptly terminated by the fault scarp north of Jamaica. The tectonic lines of Central America, according to Sapper, are of several different ages; some having been formed in the Paleozoic, others as late as the Tertiary. Possibly some of these lines continue into the West Indies with curvature convex toward the south while others turn gradually southward and become convex toward the north. Faulting in Central America may have followed along the old structural lines due to folding. The location of Guatemala in a belt of high seismicity that may be traced from the Greater Antilles through Central America and Mexico into California, together with the precipitous topography of the region suggest that the great Antillean fault system may extend into Central America, and, gradually curving toward the north, continue into California. These questions cannot be decided, however, until more field data are available.

The Sierra de los Organos, which form the backbone of western Cuba, have a northwest-southeast trend and may be genetically

[1] Sidney Powers, written communication dated September 10, 1920.

[2] Karl Sapper, *op. cit.*

[3] Sidney Powers, written communication dated September 10, 1920.

[4] T. W. Vaughan, "Geologic History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 618.

related to the tectonic lines of Central America and southeastern Mexico.

Another group of tectonic lines, prominent in the Greater Antilles, trends northwest and southeast. The principal mountains of Jamaica, composed of intensely folded Cretaceous rocks trend about N. 70° W. parallel to the northeast coast; the Grand Hilera or Sierra Cibao extend across the Island of Haiti in a northwest-southeast direction from a point near Cape Engano to Môle St. Nicolas, and the axis of elongation of Cuba from the Windward Passage almost to Habana also follows this trend. Vaughan infers that a fault runs northeast from Cape Cruz but the evidence is meager.[1]

Another old structural direction, which seems to have no relation to the present topography, is indicated by the north-south strike of the crystalline rocks exposed on the Isla de Pinos lying south of western Cuba.[2]

The Antillean fault zones cut across the earlier trend lines which seem to be due chiefly to folding, and, because of their recency as well as the magnitude of the displacements, they dominate the present topography. Transverse faulting seems to be rare, and it has had little or no effect on the topography. The irregular coast lines at the east and west ends of the various islands are in marked contrast to the rectilinearity of many of the coast lines that run east and west.

Berkey has suggested that Porto Rico is a large fault block uplifted along the southern margin and tilted toward the north with breaks at each end. In support of this hypothesis he mentions the unsymmetrical position of the main drainage divide, which is nearer the south coast; the comparatively abrupt termination of the island at both ends; and the absence of the younger limestone margin from these coasts although it is fairly continuous along the north coast and about half of the south coast.[3]

[1] T. W. Vaughan, "Fossil Corals from Central America, Cuba, and Porto Rico, with an Account of the American Tertiary, Pleistocene, and Recent Coral Reefs," *U.S. Nat. Mus. Bull. 103* (1919), pp. 288–89.

[2] C. W. Hayes, T. W. Vaughan, and A. C. Spencer, "Report on a Geological Reconnaissance of Cuba," Washington, 1901.

[3] C. P. Berkey, *op. cit.*, pp. 40–41.

In opposition to this view it may be urged that the east and west ends of Porto Rico are rather irregular; that there is neither topographic nor seismologic evidence of faulting; and that the absence of Tertiary limestones from the ends of the island may be due to submergence. The numerous reefs, projecting rocks, and small islands extending eastward from Porto Rico as far as Anegada are proof of subsidence at this end of the island; and at the other end the water is relatively shallow between Porto Rico and Haiti, averaging less than 450 m., while Mona and Desecheo islands rise above the surface. Semmes attributes the present position of the drainage divide to greater rainfall on the north side of the island.[1]

ORIGIN OF THE ANTILLEAN TROUGHS

The great troughs of the Antilles are bounded by fault zones, and are characterized by great depth, by precipitous inclosing scarps which show abrupt changes in slope at top and bottom, and by relatively flat floors that, instead of being graded like river valleys, rise and fall throughout their length. Many of the deepest places are close to the inclosing scarps instead of near the centers of the troughs, and occasional horst-like elevations are also found within the fault zones. The troughs are parallel rather than convergent and in places are roughly arranged *en echelon*.

All of the evidence is in accord with the conclusion that the troughs have been formed through faulting. Moreover, they must be attributed to subsidence of long narrow blocks rather than elevation of the areas on each side; for the rock strata exposed in the marginal scarps standing above sea-level were laid down in relatively shallow water, and portions of the larger islands have remained continuously above sea-level since pre-Tertiary time, while the faulting is more recent. The subordinate depressions at the base of the main scarps are also indicative of normal faulting, and there is an absence of lateral pressure effects such as would be expected to accompany thrust faulting.

Vaughan is of the opinion that the faulting took place in late Tertiary, probably Pliocene time, and he cites three kinds of evi-

[1] D. R. Semmes, "The Geology of the San Juan District, Porto Rico," *Scientific Survey of Porto Rico and the Virgin Islands, N.Y. Acad. Sci.*, Vol. I, Part I (1919), p. 38.

dence, namely: (1) The faulting along the south coast of Cuba is subsequent to old or middle Miocene, as the Miocene La Cruz marl is abruptly cut off at the shore; (2) the sea has had time to cut only narrow benches into the fault scarps that form shore lines; and (3) the biological evidence demands land connection in late Tertiary time between Cuba, Santo Domingo, Porto Rico, and thence to South America.[1]

The faulting may date from the Pliocene, as suggested by Vaughan but the frequent occurrence of earthquakes along the fault zones proves that the displacements are still continuing; and the sea-waves, which have accompanied nearly all of the great earthquakes with the exception of those originating in the Haitian land valleys, indicate that these latest displacements have also been vertical. Another evidence of recent displacements is furnished by the character of the material on the sea-floor along the fault zones. Off the northwest coast of Porto Rico broken coral is found at a depth of 1,864 m. and the bottom is "rocky" at 3,221 m.[2]

The Antillean fault system, whether it continues into Central America or not, forms one of the major structural features of the earth; and the displacements now going on are similar to those which have occurred in the past. The earthquakes are not limited to the immediate vicinity of land areas and hence cannot be attributed to adjustments resulting from changes in surface-loading due to erosion. That the faulting extends to profound depths is shown by the persistence of the fault zones, by the great height of the scarps, and by the extrusion of lava from some of the fault fractures.

The total volume of lava that has reached the surface along the Antillean fault zones is insignificent as compared with the size of the troughs; consequently there can be in this instance no causal relation between volcanic activity and the foundering of the narrow blocks, such as has been suggested for the Christiania Fiord in southern Norway, the "rift valley" of eastern Africa and similar troughs elsewhere.

[1] T. W. Vaughan, "Geologic History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 626.

[2] United States Coast and Geodetic Survey Chart 901.

Fault phenomena of the type exhibited in the Antilles testify to a state of tension rather than compression in the earth's crust. This tension is difficult to explain. It may be due to warping, for there is some evidence that the formation of the troughs has been accompanied and perhaps, in part, preceded by an upswelling or arching of the region together with more or less subsidence of the border portions. The uplift has culminated in the Island of Haiti, and the Bartlett Trough has developed along the axis of uplift, the surface being in most places higher near the borders of the trench than farther back. Sea-terraces, marking intermittent elevations have been observed along many coasts of the Antilles; in Cuba they extend entirely around the east end of the island but attain their finest development along the south coast between Cape Maisi and Guatanamo.[1] On the opposite side of the trough near Montego Bay, Jamaica, they are also well developed, Hill having observed six distinct benches.[2]

While the evidence is extremely meager it is at least in accord with what is known concerning the structural relations of fault troughs in the other parts of the earth. Most of these troughs appear to have been formed as a result of the upswelling of broad arches and plateaus of the downwarping of basin-like areas under the influence of forces that probably have acted vertically.

[1] R. T. Hill, *Cuba and Porto Rico with the Other Islands of the West Indids*, p. 44, New York, 1899.

[2] R. T. Hill, "The Geology and Physiography of Jamaica: Study of a Type of Antillean Development," *Bull. Mus. Comp. Zoöl. Harvard College*, XXXIV, Geol. Ser. 4 (1899), p. 31.

THE CHARACTER OF THE STRATIFICATION OF THE SEDIMENTS IN THE RECENT DELTA OF FRASER RIVER, BRITISH COLUMBIA, CANADA[1]

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OUTLINE

INTRODUCTION
FRASER RIVER AND ITS RECENT DELTA
PITT LAKE DELTA
CHARACTER OF STRATIFICATION OF THE SEDIMENTS
SUMMARY OF CONCLUSIONS

INTRODUCTION

During the course of an investigation, carried on during parts of 1919 and 1920 by the Geological Survey of Canada in co-operation with the Department of Public Works, of the characteristics of Fraser River, British Columbia, an opportunity was afforded of studying the character and mode of origin of the stratification of the sediments forming the Recent delta of the Fraser. Bottom samples were obtained by means of a bottom-sampling machine which furnished core samples (1) from the sea-bottom deposits in the Strait of Georgia, and (2) from the fresh-water deposits in Pitt Lake, a tidal lake tributary to the Fraser. The object of this paper is to describe the character and mode of origin of the stratification of the Recent delta deposits of the Fraser River, and to contrast the character of the stratification of the sediments being formed in fresh water with that of the sediments being formed in salt water.

The writer is indebted to Dr. W. Bell Dawson, superintendent of the Tidal and Current Survey, Department of the Naval Service, Canada, for information regarding the tides and tidal currents in Fraser River and in Pitt Lake, and to Mr. C. C. Worsfold, district engineer, Department of Public Works, Canada, for information regarding the tides and freshets in Fraser River.

[1] Published by permission of the Director of the Geological Survey, Canada.

FRASER RIVER AND ITS RECENT DELTA

The Fraser River is the largest river in British Columbia whose basin lies entirely within the province. It has a length of 790 miles and drains an area of 91,700 square miles. The maximum discharge of the river at Hope (100 miles above its mouth) for the past nine years, as determined by the Dominion Water Power Branch of the Department of the Interior, was in July, 1920, when it amounted to 380,000 c.f.s. During the great flood of 1894, however, the discharge as estimated by officials of the Department of Public Works was nearly 500,000 c.f.s. The average minimum discharge of the river at Hope for the past nine years was 17,000 c.f.s., the lowest being 12,000 c.f.s. There is thus considerable variation from high to low water in each year. The water usually begins to rise in May and reaches its greatest height in June or July. Extreme low water may occur in any month from November to March. During the low-water period the river is affected by ocean tides for a distance of 60 miles above its mouth. The current is reversed in the river by the flood tide, however, only for 30 miles above the mouth. The tides in the Strait of Georgia are declinational in character and are characterized by marked diurnal inequality of the semidaily tides. The mean range at the mouth of the Fraser River is 6.4 feet. The maximum range of the great flood tides is 15 feet and of the great ebb tides 14 feet. These maximum ranges, however, are rarely reached, the average for the large tides—which occur for a few days twice a month near the time of maximum declination of the moon—being about 12 feet for the ebb tides and 13 feet for the flood tides. During the balance of the month the ranges are less. The fact that the river is tidal for a considerable distance above its mouth renders it navigable; for the lack of river water during the low-water stage of the river is largely compensated by the tidal water. The combined ebb-tidal and river discharge of the river, in the main channel near its mouth, is rarely less than 100,000 c.f.s., even during the extreme low-water stage of the river.

The water of the Fraser River is turbid to some extent throughout the year, and is markedly so during freshets; but the amount of material carried in suspension is comparatively small. The

average amount of material carried in suspension, as shown by analysis of composite samples of the river water collected triweekly at New Westminster for the period of one year from June 5, 1919, to June 5, 1920, was 62 parts per 1,000,000, and the maximum 230 parts per 1,000,000. The high turbidity of the water is due to comparatively large amounts of very fine material carried in suspension. About half the material carried in suspension during the freshet is composed of silt and clay, a part of which is so fine that it can with difficulty be removed by filtering. The river in its seaward part carries in suspension little material coarser than very fine sand (0.1 to 0.05 mm.), but considerable quantities of medium and coarse sand are moved along the bottom. During the freshet the turbid river water flows out over the sea water in the Strait of Georgia and extends for distances of 10 to 15 miles from the mouth of the river. The color line marking the contact of the river water and the sea water is a striking feature in the Strait of Georgia, near the mouth of the river, where it oscillates backward and forward according to the varying influences of the river, tidal, and wind-induced currents.

The velocities of the currents in the lower part of the river near its mouth vary greatly with the tides and according to the stage of river water. During the freshet the maximum velocity of the combined river and ebb-tidal currents reaches, but rarely exceeds, $5\frac{1}{2}$ knots per hour. During the low-water stage the maximum velocity is about $3\frac{1}{2}$ knots. The inward-flowing flood-tidal current rarely, even during the lowest stage of river water, equals the outward current, although the rise of tide on the flood is more rapid than the fall on the ebb. The ebb-tidal current is the dominant current because it is reinforced by the river current. The sea water enters the river during the freshet only to a very small extent, and only along the bottom of the main channel. During the low-water stage the sea water at times extends on the flood tide as much as 8 miles up the river. The flood-tidal current in the Strait of Georgia runs north and is the dominant tidal current. It has a maximum velocity of about 2 knots. Slack water is very pronounced in the lower part of Fraser River, because of the lack of a deep channel where it enters the river, which

prevents sea water from entering the river in flood tide until the tide has reached a considerable height.

The Recent or modern delta of Fraser River has its head, as defined by the point where the first distributary is given off, at the city of New Westminster. It extends west for 19 miles to the Strait of Georgia and, across its seaward front, is 14 miles wide. The surface of the delta is all below the level of high tide, except in a few places, where the surface of peat bogs is a few feet above the general level and the delta land high enough to be reclaimed; this is diked to exclude the flood-tidal and freshet waters. At New Westminster the river is confined between drift ridges or upland areas, which rise 200 to 300 feet above the river. The upland area south of the river marks the inner edge of the delta and extends from a point on the river $3\frac{1}{2}$ miles below New Westminster nearly straight south to Boundary Bay. The delta is bounded on the north by the highland area extending from New Westminster nearly west to Point Grey. In its seaward part on the south side it is interrupted by the highland area of Point Roberts, an island-like drift hill, which has been joined on to the mainland by the construction of the delta. The North Arm of the Fraser flows along the northern border of the delta, the main Fraser flows through the central part, and in the southern part there are a number of smaller outlet channels.

There can be no doubt that the materials composing the delta have been transported to their present resting-place very largely by the river; for it has been shown that the river transports considerable material during its freshet stage, and there is no other apparent source for such a large amount of material. A small part, however, has been and is being derived from wave erosion of the shores, chiefly of the highland area of Point Roberts. A large part of the material composing the delta is sand and silt derived by stream erosion from the vast accumulations of glacial drift which border the banks of the Fraser and Thompson rivers for long distances above the canyon of the Fraser, in smaller part from erosion of the bedrock (granite) in the canyon of the river, and from erosion of the drift deposits in the upper part of the delta area.

The delta is building out into fairly deep water in the Strait of Georgia in spite of the facts that the river is tidal for a considerable distance above its mouth, with a mean tidal range of 6.4 feet and a maximum range of 15 feet at its mouth, and that the seaward front of the delta is swept by fairly strong tidal currents. The outbuilding occurs because of the dominance of the river currents over the tidal currents. The river currents are strong enough to transport large quantities of coarse and fine material which the tidal currents cannot transport into deep water. The tides and tidal currents have the effect, however, of giving an unusual form to the seaward portion of the delta. In its seaward portion the river flows for several miles through sand banks exposed in large part at low tide, but completely submerged at high tide. These banks extend seaward on an average of 4 to 5 miles from the higher delta land and are for the most part nearly level except where channeled by outlet streams. The flood tides and tidal currents tend to cause a diffusion and diversion of the river currents in this part of the delta and prevent the river from building up its banks. The coarse material in the sand banks is gradually moved seaward by the dominance of the combined ebb-tidal and river currents, which tend to carry it seaward, over the flood-tidal currents moving inward. The fine material is kept in suspension until it is carried seaward by the river currents and settles by gravity and through the influence of sea water in causing it to flocculate, or is carried inshore by the flood-tidal or wind-induced currents and lodges in the grass-covered marshes and slack-water channels, tending to build them up and extend the higher delta land seaward. The flood-tidal currents also have the effect of giving to the greater part of the subaqueous front of the delta a smooth, curved outline lacking the finger-like projections characteristic of many deltas.

In structure, the delta presents the forms characteristic of a high-grade delta built into fairly deep water. The fore-set beds are well developed and extend from the 3-fathom line to about the 30-fathom line and have an average dip of about 10°. The dip, however, is irregular, and in places the subaqueous front of the delta is nearly vertical for heights of 1 to 3 fathoms. Below the

30-fathom line the beds slope more gradually seaward, the 100-fathom line being reached at from 1 to 2 miles from the outer edge of the sand banks. The horizontal bottom-set beds, consisting of very fine material, occupy the bottom over a considerable part of the Strait of Georgia, off the mouth of the river. The strait, which is 10 to 15 miles wide, varies in depth in its central part from 100 fathoms to about 225 fathoms. The top-set beds are thinnest and in most places only a few feet in thickness. In places, however, they may be upward of 100 feet thick, as, for example, where a deep channel of the river has been abandoned and has been gradually filled and built up to high-tide level. The top-set beds are sandy in character in their lower part up to about half-tide level, the upper part being silty in character. The silty, fine-grained beds, formed by deposition from flood waters overflowing the river banks, become thicker, progressively, upstream, owing to the fact that freshet waters do not affect the level of high tide in the lower part of the river as far up as Steveston, 6 miles above the mouth, but appreciably affect the level in the upper part of the river. The shore face of the delta is very weakly developed because wave action has little effect owing to the shallowness of the water over the sand banks.

The river, for a distance of 40 miles above New Westminster, is in places bordered by extensive flats, mostly below high-tide, freshet level, which have been formed by the meandering of the river and its tributaries, and by deposition from flood waters. The flats, for the most part, have been carved out of the raised Pleistocene marine clays and delta deposits and form the alluvial flood plain of the river.

PITT LAKE DELTA

An unusual kind of delta is being formed at the lower or south end of Pitt Lake, which drains south by way of Pitt River into the Fraser above New Westminster. The lake is $\frac{1}{2}$ to $2\frac{1}{2}$ miles wide and 15 miles long, and is tidal. During the freshet stage of the Fraser the surface of the water in Pitt River and Pitt Lake is raised several feet above the normal level and falls only slightly with the tides, so that during this time there is very little current into or out of the lake. During the low-water stage, the tides in

the lake have a maximum range of about $3\frac{1}{2}$ feet, and there are strong currents both ways. The delta is being built into the lake at the south end, although the drainage of the lake basin is outward or toward the south. This is the case because the inward, flood-tidal current is stronger than the outward current, because the rise of tide on the flood is more rapid than the fall on the ebb, and the outflow of river water is not great enough to counteract this effect.

The delta is partly submerged and extends about 4 miles into the south end of the lake. The top-set beds are exposed in places at extreme low tide, but are for the most part covered by 3 to 6 feet of water. A single, straight river channel extends through the delta. The delta has advanced along the line of the channel and left unfilled a deep depression on its west side. The fore-set beds are well developed and extend to depths of 20 to 30 fathoms, the slope being in places as much as 30°, but for the most part only about 10°. The lake has a maximum depth near its south end of about 50 fathoms. In the narrow parts near the north end the maximum depth is about 80 fathoms.

CHARACTER OF STRATIFICATION OF THE SEDIMENTS

A number of core samples of bottom deposits in the Strait of Georgia, off the mouth of the Fraser and in Pitt Lake, were obtained by means of a bottom-sampling machine. The machine consisted of a hollow casting, 3 feet long, sharpened at the lower end and fitted at the top with a ball valve which worked automatically. The machine weighed 55 pounds and was operated from a motor boat by means of a sounding machine of the ordinary type. The samples were mounted in plaster of paris and sectioned vertically to show the character of the stratification. A number of the samples are shown in Figures 1 and 2.

The stratification of the top-set beds of the Fraser Delta and alluvial flood-plain deposits differs in different parts of the vertical section. Below the level of mean low tide the top-set beds are composed largely of sand, are for the most part horizontally bedded, but in places are cross-bedded and current-ripple-marked. In places there are thick and thin lenses or beds of silt and clay which

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FIG. 1.—Core samples of sediments being formed in the Recent delta of Fraser River, British Columbia, Canada. The samples are mounted in plaster of paris and have been sectioned vertically to show the character of the stratification.

show no definite lamination. The stratification of the sandy beds is in places rendered visible by thin partings of silt and clay. The stratification of the beds in the intertidal zone is very marked, the characteristic feature being a very thin tidal lamination. Bottom sample No. 1, shown in Figure 1, illustrates the character of the stratification of part of the beds in the intertidal zone. The light-colored parts are silty in character and the dark parts are sandy. The seasonal character of these beds is indicated in places by layers of vegetable matter, and in other places by the different character of the laminae formed during the freshet stage of the river, from those formed during the low-water stage. During the freshet the water holds in suspension considerable quantities of silt, and during the low-water stage it is nearly clear. Hence the laminae formed during the freshet are largely silt, and those formed during the low-water stage are largely fine sand. The tidal laminae average possibly 15 to 20 to the inch. The seasonal layers average about 5 or 6 to the foot. But as contemporaneous erosion and deposition are constantly going on, any one section gives a very incomplete record of either the tidal laminae or seasonal layers.

The stratification of the alluvial flood-plain deposits differs from that of the tidal flood-plain deposits because of the fact that during the freshet the surface of the part of the river above New Westminster is raised above the normal level and falls very little with the tides. Hence, during the freshet, a single layer of silt, which may be as much as ½ inch in thickness, is deposited on the alluvial flood plain. Neither the tidal nor the alluvial flood-plain laminae show any marked gradation upward from coarse to fine particles in the individual laminae.

The character of the stratification in the fore-set beds of the Fraser Delta is indicated approximately in samples Nos. 6, 7, and 8 shown in Figure 1. The beds are composed of a mixture of fine sand (0.1 to 0.05 mm.), silt (0.05 to 0.005 mm.), and clay (less than 0.005 mm.). They are, for the most part, thinly laminated, in a somewhat similar manner to the tidal flood-plain deposits. In places the lamination is even, in other places it is markedly irregular, and cross-bedding as well as inclined bedding occurs. The lamination is tidal in character, but is the result of the com-

FIG. 1.—Core samples of sediments being formed in the Recent delta of Fraser River, British Columbia, Canada. The samples are mounted in plaster of paris and have been sawed vertically to show the character of the stratification.

bined effects of flocculation in sea water, river and tidal currents, and slack water. A leaf bed is shown in sample No. 7 at about mid-length. As it is known from a comparison of soundings made in 1859 and shown on the 1860 chart with those made in 1919 by the Hydrographic Survey of Canada that sedimentation takes place in the fore-set beds, at the points where the samples were taken, at the average rate of about 20 feet per year, it is obvious that the samples would not show evidence of seasonal banding. It is known that coarse material is deposited off the mouth of the river during the freshet, and that this is overlain by finer materials deposited during the low-water stage. Hence the bedding probably has in places a seasonal character, but the annual layers vary in thickness, in different parts of the delta front, from a few inches or even less to as much as 50 feet.

Bottom samples Nos. 9 and 10, shown in Figure 1, are from the fine-grained bottom-set beds of the delta, in the Strait of Georgia. Sample No. 9, from a depth of 70 fathoms, is largely silt, and sample No. 10, from a depth of 92 fathoms, is largely clay, which, because of excessive shrinkage in drying, is badly cracked. The samples as mounted and shown in the figures are smaller in size than in the original state because of compression and shrinkage in drying. Sample No. 10 is most compressed, and, judging by the depth of penetration indicated by the mark left on the outside of the sampling machine, is one-half to two-thirds of its original length. The other samples are more nearly representative of the original thicknesses.

A marked feature of the bottom samples from the fine-grained bottom-set beds is the absence of any trace of lamination either in the beds composed of silt with a mixture of very fine sand, or in the beds composed for the most part of clay. The lack of lamination is due to the well-known effects of flocculation in sea water, which causes the fine silt and clay particles in suspension in the river water to settle to the bottom together when flocculation takes place as the result of the mixing of the two waters. In places also very fine sand settles to the bottom along with the silt and clay. Hence, in the case of the fine-grained materials deposited in sea water, there is a lack of sorting and no definite lamination,

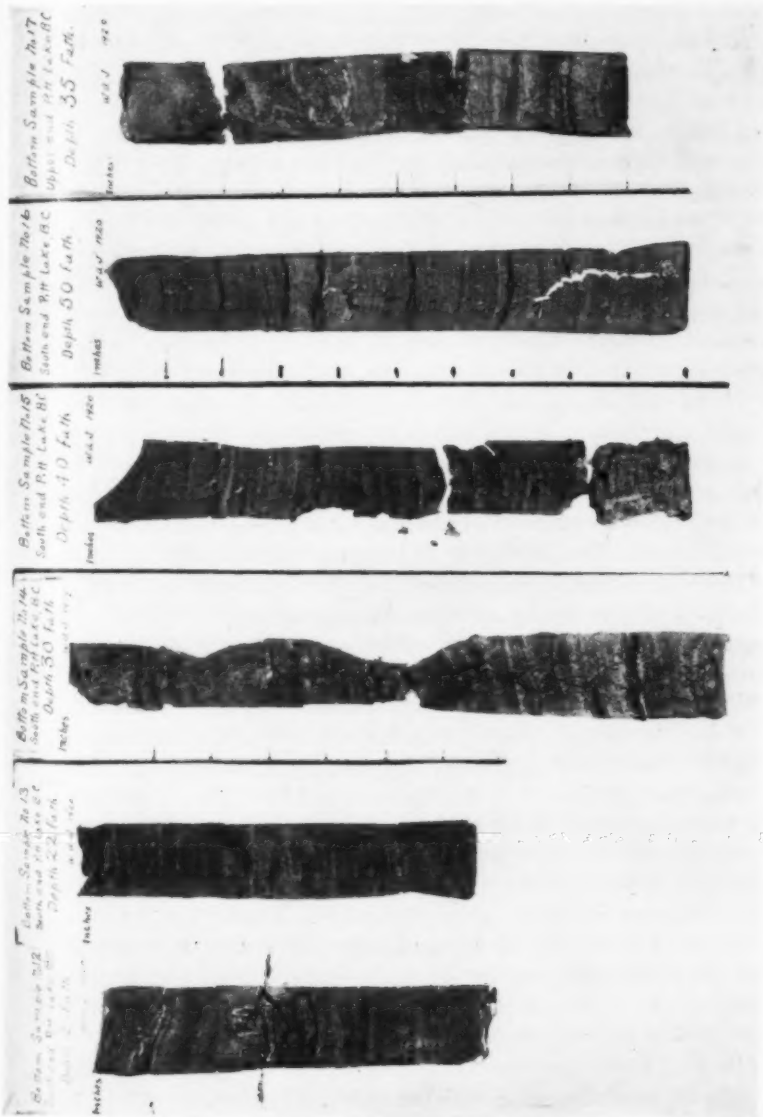

FIG. 2.—Core samples of sediments being formed in Pitt Lake, British Columbia, Canada. The samples are mounted in plaster of paris and have been sectioned vertically to show the character of the stratification.

and the beds are probably thick and massive. As the samples from the bottom-set beds were taken at points where sedimentation is taking place at the rate of at least 1 foot per year, they cannot be taken as criteria of the presence or absence of seasonal banding. It is possible that in places the bedding is seasonal in character, for coarser material is carried out into the strait during the freshet than during the low-water stage of the river.

Samples from the bottom of Pitt Lake are shown in Figure 2. Sample No. 12 is from the submerged top-set beds, samples Nos. 13 and 14 are from the inclined fore-set beds, and samples Nos. 15 and 16 are from the bottom-set beds of the delta at the south end of the lake. Sample No. 17 is from the bottom-set beds of the delta formed by inflowing streams at the north end of the lake.

The character of the stratification of the deposits formed in the tidal fresh-water body differs in several ways from that of the deposits formed in salt water in the Strait of Georgia. Tidal laminae are shown to some extent in all the samples from Pitt Lake. They are exceedingly fine, being in places as many as 100 to the inch. The bedding of the fore-set beds is much more even than that of the fore-set beds of the Fraser Delta, apparently because of the absence of tidal currents along the front of the delta. Samples Nos. 13, 14, and 15 (Fig. 2) were taken at the south end of the lake near the subaqueous front of the delta. They all show a fairly regular recurrence of silty layers (light-colored) separated by sandy layers (dark colored). This banding is probably tidal in character and may be explained as follows. There are two tides daily in Pitt Lake, but one is so small that as a rule the current is not reversed; so that there is nearly always only one period of outflow and one of inflow each day. Large tides occur twice a month near the times of maximum declination of the moon, and small tides occur near the times when the moon is over the equator. The inward current is greater at the period of large tides than at that of small tides. During the times of large tides sand tends to be deposited, and during the times of small tides silt tends to be deposited. The sandy bands separating the silty bands are very thinly laminated and in places contain eight or ten laminae. The silty bands also are in places thinly

laminated, but not so definitely as the sandy bands. The rate of deposition in the Pitt Lake Delta is not definitely known, but probably is very small, for a comparison of a number of soundings taken in 1920 with those taken in 1860 shows no great difference. The soundings taken at the point, about 1 mile from the front of the delta, where sample No. 16 was obtained, showed that deposition had taken place to a depth of 5 to 10 feet during the past 60 years, or at the rate of 1 or 2 inches a year. The rate of deposition near the front of the delta is probably much greater. The beds probably show therefore both tidal lamination and tidal banding. They apparently do not show seasonal banding. From the fact that there is very little current in the entrance to Pitt Lake during parts of May, June, and July when the Fraser is in flood, it might be expected that this period would be indicated in the bottom samples by a thick layer of silt. During this period, however, the turbid water of the Fraser does not enter Pitt Lake to any extent and the lake water is nearly clear.

Bottom sample No. 16, taken at a depth of 50 fathoms, is from the bottom-set beds of the delta, in the deepest part of Pitt Lake, near the south end. It is composed of silt and clay and differs markedly in the character of its stratification from the fine-grained samples from the bottom-set beds of the Fraser Delta in the Strait of Georgia in that it is thinly and gradationally laminated. The lamination is probably due to tidal action and to the absence of flocculation of the fine material in suspension in the fresh water, which permits the silt and clay to settle to the bottom at different rates.

Bottom sample No. 17, taken at a depth of 35 fathoms, is from the bottom-set beds or from near the contact of the fore-set bottom-set beds of the delta at the north end of Pitt Lake. It shows in places a tidal lamination and probably also a seasonal banding. There is a fairly regular recurrence of silty layers $\frac{1}{2}$ to 1 inch, separated by sandy layers 1 to 2 inches thick. The silty layers were probably deposited during the freshet when the surface of the lake did not rise or fall appreciably with the tides, and the sandy layers during the periods when the lake was affected by the tides; for at ebb tide the currents in the streams flowing through the

delta at the north end of the lake are greatly increased. This appears to be borne out by the fact that in places the sandy layers are thinly laminated.

SUMMARY OF CONCLUSIONS

The tidal flood-plain deposits of the Fraser River are characterized by a very thin lamination which is tidal in origin. The seasonal character of the bedding is shown in places by layers of vegetable material and in other places by alternations of silty layers and sandy layers, both of which show tidal lamination.

The alluvial flood-plain deposits of the Fraser are characterized by seasonal layers of silt and vegetable material.

Neither the tidal nor the alluvial flood-plain deposits show to any marked extent gradational lamination.

The fore-set beds of the Fraser Delta, deposited in sea water, are characterized by a thin lamination which is the result of the combined action of flocculation in sea water, river and tidal currents, and slack water. The beds have in places marked cross-bedding as well as inclined bedding. The fine-grained bottom-set beds are thick and without lamination, because of the effect of flocculation in sea water.

The Pitt Lake Delta deposits formed at the south end of Pitt Lake (a tidal fresh-water lake) are characterized by a very thin lamination and by a banding, both of which are probably tidal in origin. The fine-grained bottom-set beds have a very thin and gradational lamination, which is due to tidal action and to the absence of flocculation in fresh water. They show no definite evidence of seasonal banding. The deposits now forming in the delta at the north end of Pitt Lake have a tidal lamination and probably also a seasonal banding.

A conclusion which may be drawn from the fact that the fine-grained sediments deposited in salt water are not laminated, because of the effects of flocculation, while those formed in fresh water are, is that fine-grained sediments which are evenly and gradationally laminated are fresh-water sediments in origin or, if marine in origin, are glacial; for it is probable that sea water would

be sufficiently dilute to prevent flocculation and hence to permit of lamination of the sediments only at times when and in places where large volumes of water from melting ice sheets were being poured into the sea. A possible exception might occur in places where large volumes of river water are being poured into an estuary or into a nearly land-locked part of the sea; but flocculation takes place in the Strait of Georgia in spite of the large volume of fresh water brought down by the Fraser, and where the density of the surface sea water is only 1.010, as compared with the density of normal sea water which at 17.5° C. is 1.027.

THE STRUCTURAL RELATION OF THE PURCELL RANGE AND THE ROCKY MOUNTAINS OF CANADA

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It has been found repeatedly, in recent years, that on the flanks of many elongated mountain ranges there are thrust faults dipping in under the range. In the absence of these faults, overturned folds, with their axial planes dipping into the range, and indipping slaty cleavage are common. Partly from observation of this sort, Dr. R. T. Chamberlin developed his hypothesis of the wedge-shaped zones of deformation in mountain building.[1] With this idea in mind, I attempted to determine whether the Rocky Mountain trench, a long, narrow depression between two mountain ranges, would show a connection with this type of structure.

This great valley has a length of about 800 miles. It starts somewhat south of the boundary line between the United States and Canada and runs in almost a straight line to the northwest between the Rocky Mountains on the east and a succession of ranges on the west. From what is known about the trench it has been estimated to have an average width from wall to wall of 5 miles. The portion of the trench which I studied was from Gateway, Montana, at the boundary line, to Golden, British Columbia, 180 miles to the north. Study of the trench has been hitherto quite limited. Dr. Daly's section at the 49th parallel[2] crosses the trench, Dr. Schofield's "Cranbrook Area"[3] borders the west side of it for about 60 miles, and the section along the main line of the Canadian Pacific across the Cordillera, made by Allen and Daly,[4] crosses it about 200 miles north of the boundary. Others have made rapid reconnaissances of the trench.

[1] R. T. Chamberlin, *Jour. Geol.*, Vol. XVIII (1910), p. 228.

[2] R. A. Daly, *Geol. Surv. Can. Mem. 38* (1912).

[3] S. J. Schofield, *Geol. Surv. Can. Mem. 68* (1915).

[4] *Guidebook No. 8*, Congrès Géologique International, 1913.

In the 180 miles which I studied, there are two distinct geographic provinces. In the northern province, which extends as far south as Canal Flats, the trench is drained by the Columbia River which has its source in Columbia Lake just north of the Flats. The valley is narrow, for the most part not more than 3 or 4 miles wide. In part of this northern zone there is a wide valley west of and parallel to the Columbia Valley, which joins the trench at both ends and is only separated from it by a narrow ridge, broken in one place. South of Canal Flats the valley is drained by the Kootenay River, which comes into the trench from the east and flows south. In this portion the trench becomes much wider till it reaches its maximum width of 16 miles at Fort Steele. South of there it contracts rapidly to 5 miles at Bull River, but widens again at Elko and at Gateway.

From what could be deciphered from the stratigraphy, it was found that there are two principal series of rocks represented. One is a great succession of limestones ranging from the upper Cambrian to the Mississippian, but with rather large stratigraphic disconformities. The other series is dominantly clastic, consisting chiefly of various metamorphic phases of sandstone, shale, and conglomerate. It has recently been determined, in at least some cases, to be Cambrian, but probably includes much pre-Cambrian. Probably its age overlaps somewhat that of the limestone series. As shown on the map (Fig. 1), this last series makes up most of the west side of the trench in the northern zone, while the limestones are on the east side and occasionally overlap to the west side. South of Canal Flats the limestone series retreats into the Rocky Mountains, and the clastic series crosses the trench, and occupies a zone about 12 miles wide on the east side. Farther south, between Bull River and Gateway, the limestone series again appears in various hillocks in the trench and in narrow zones along its sides.

Structurally the trench has hitherto been considered as a sort of Graben[1] or at least the product of normal faulting.[2] The results

[1] R. A. Daly, *Geol. Surv. Can. Mem. 38*, p. 600.

[2] S. J. Schofield, "The Origin of the Rocky Mountain Trench," *Trans. Roy. Soc. Can.*, Sec. 4 (1920), pp. 73–81.

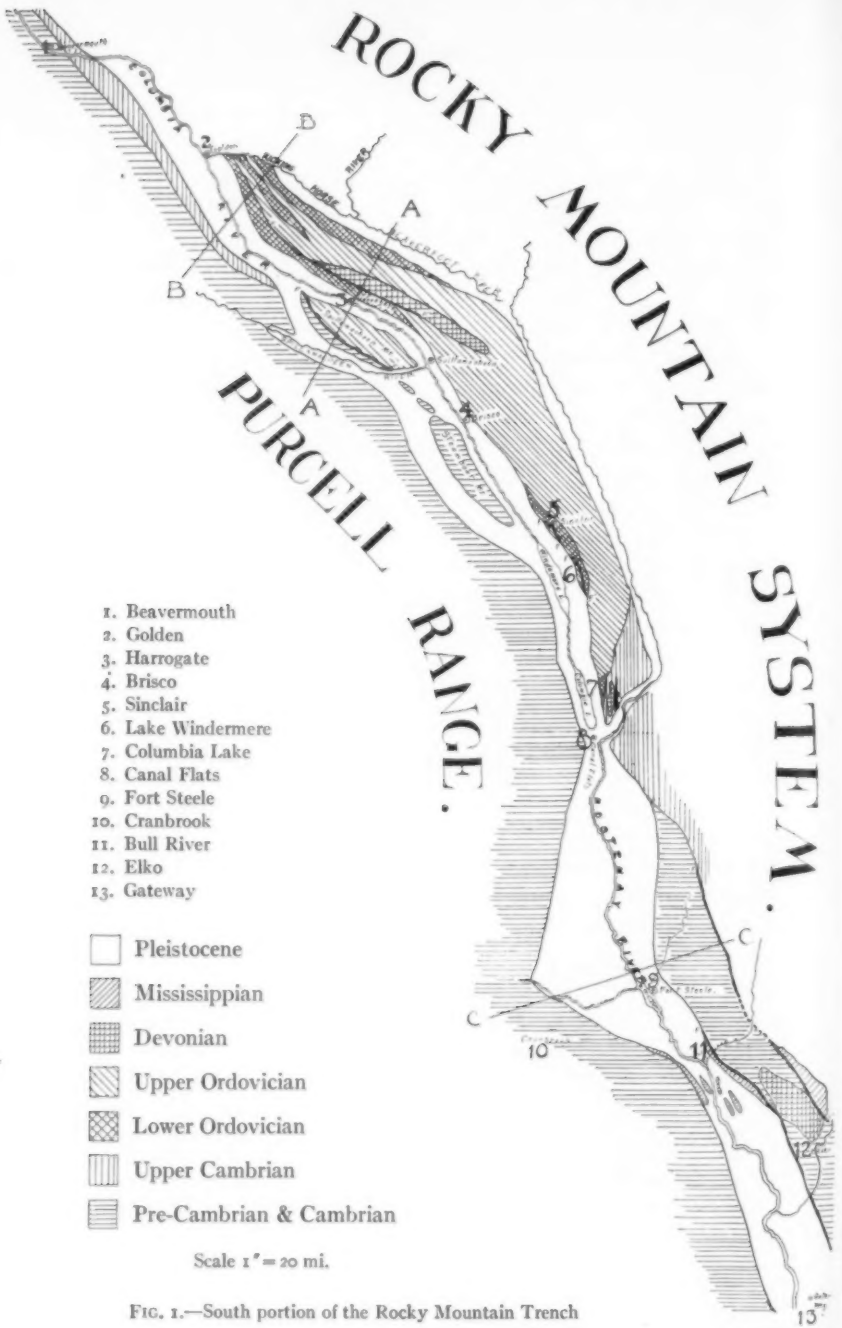

FIG. 1.—South portion of the Rocky Mountain Trench

of my study do not harmonize with this view. The structure should be considered in three divisions.

1. *The northern part.*—In the northern part, the trench is certainly defined by structural features. While the structure varies considerably, there are some features which hold for the entire distance. There is, for example, intense folding on both sides of the trench. The axes of the folds in most cases dip away from the trench, and in places are overturned (Fig. 2).

Most of the faults are thrust faults. On the west side most of these have west-dipping fault planes. On the east, most of the

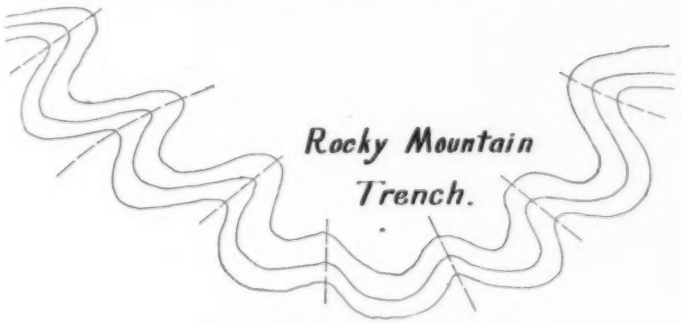

FIG. 2.—Ideal section of folding

thrusts have east-dipping planes. There is a very large thrust fault, which either borders or is found in the trench from Canal Flats almost to Parsons. This fault causes the semimetamorphic series of pre-Cambrian and early Cambrian age to be thrust over against the topmost beds of a thick Ordovician series on the east. At Harrogate (Fig. 3) there are two west-dripping thrust faults each with a displacement of more than 6,000 feet. This great fault probably does not exist north of Parsons. At Beavermouth, 25 miles northwest of Golden, Daly considered that the upper Cambrian-Ordovician series on the east was separated from the Cougar Quartzite on the west by a normal fault of 15,000 feet displacement. In a section in Canyon Creek (Fig. 4) near Golden, the same formations were found as those occurring on the two sides of the fault at Beavermouth, and here there is no fault and the formations follow each other in normal stratigraphic succession.

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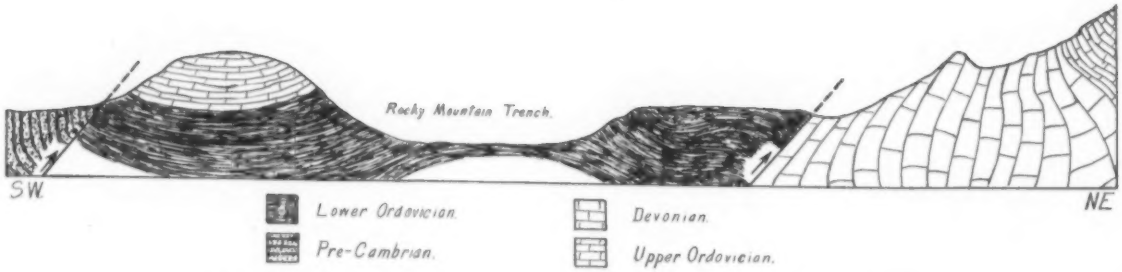

FIG. 3.—Section at Harrogate (through *A*—*A*, Fig. 1). Scale: 1 inch = 1.06 miles

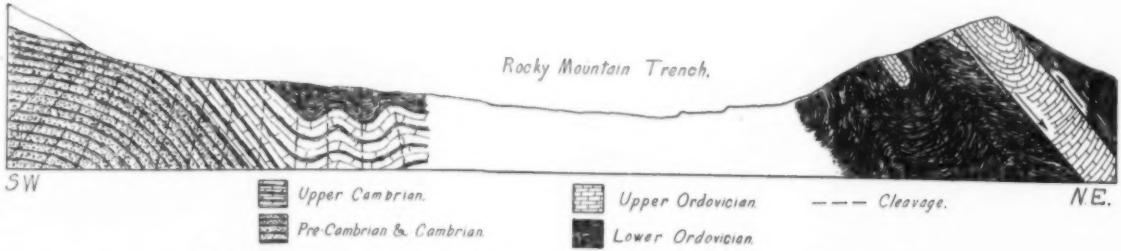

FIG. 4.—Section at Canyon Creek (through *B*—*B* Fig. 1). Scale: 1 inch = 1.2 miles

At Beavermouth there is a wide zone separating the two series in question, and the fault was inferred entirely on lithological grounds. It seems unlikely that such a fault exists. As will be seen from the section, thrust-faulting on the east is important in this region, which is rather significant in view of the dying out of the west-dipping thrust faults.

In the southern portion of this northern zone there are cases on the east side of the trench where there are intersecting east- and west-dipping thrust faults. In all such cases the west-dipping thrusts cut those from the east. There is an interesting example

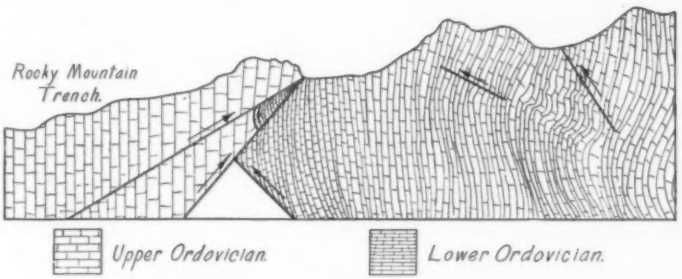

FIG. 5.—Section at Sinclair

of this at Sinclair Springs (Fig. 5). To the east the west-dipping thrust faults always become less conspicuous, and finally die out. At Brisco an east-dipping thrust fault was found on the west side of the trench. Thus there is considerable intersection of the east- and west-dipping thrust faults.

If the general rule for thrust faults is to have dips of much less than 45°, then these faults are exceptional since their dips average about 50° and in some cases are as high as 70°. This is in contrast to the low dips of the thrust faults on the east side of the Rockies in the northern United States and Canada. Experiments, on folding and faulting, which I have made, show that faults which develop at the intersection of two folds may have dips which exceed 45° due to the upward relief being much easier than the lateral. The faults developing between two separate mountain ranges might be subjected to the same influences.

The age of the faulting is not known definitely, but there are several factors bearing on the age, which should be mentioned. In the first place the faulting must have been subsequent to most of the folding in the Rocky Mountains, because in almost no instances are the fault planes involved in the severe folding found on the east side of the trench. The folding of the Rockies is thought to have been mostly during the Laramide revolution. In several cases thrust faults of very great throw were found to exist in such a location that the upthrow side of the thrust is in the valley, while the downthrow side forms the mountain wall (Fig. 3). This feature was found in so many cases that it is obvious that faulting does not directly control the topography. Therefore this faulting must be old. It seems probable that it took place in early Eocene times, at the close of the Laramide deformation. If the overthrusts on the east side of the Rockies are contemporaneous with those on the west, the great amount of subsequent erosion lends some weight to the problem of the age of the Lewis overthrust, which has been considered either early Eocene or Miocene.[1]

The slaty cleavage found in the vicinity of the trench in this section is very constant in character in that it persistently dips to the east on the east side of the trench, while on the west side it dips to the west. Up Canyon Creek, where the section was almost uninterrupted, the cleavage, as shown by the dotted lines (Fig. 4), dips to the west in the Purcell Mountains, becomes gradually vertical toward the middle of the trench, and farther east dips at high angles to the east. Across the trench the cleavage dips to the east at lower angles.

Thus the folding, the thrust-fault system, and the slaty cleavage all point toward the indipping structures and are evidence in favor of Chamberlin's hypothesis of the wedge-shaped deformation masses formed in mountain-building. Here in the trench two intersecting wedges occur, one the Rocky Mountain and the other the Purcell-Selkirk system. The great overthrusts on the east side of the Rockies, such as the Lewis thrust and the Cascade Mountain

[1] B. Willis, *Bull. Geol. Soc. of America*, Vol. XIII (1902), p. 333; R. A. Daly, *Geol. Surv. Can. Mem. 38*, pp. 90–95.

thrust, are examples of indipping structure on the other side of the Rocky Mountain wedge.

The cause of this valley in the northern section is partly the zone of weakness produced by the intersection of such a large number of fault planes, causing erosion to be more rapid here than elsewhere. Also the type of folding on the sides of the trench produced a depression between (Fig. 2).

South of Canal Flats the zone which separates the structure of the Rocky Mountains from the Purcell Range leaves the trench, and swings to the east. This zone does not die out, but appears in the Hughes Range of the Rockies some 12 miles from the trench. It was traced as far south as Elko. In at least two places, this zone has overthrust faults from the west. Fifteen miles up into the

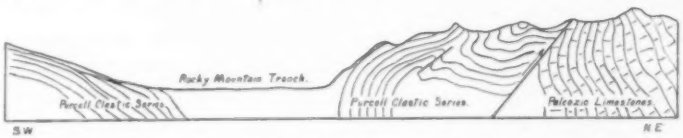

FIG. 6.—Section at Fort Steele (through *C*—*C*, Fig. 1). Scale: 1 inch = 14.63 miles.

Rockies from Fort Steele, there is an overthrust with a throw of several thousand feet (Fig. 6). No valley exists along this fault, which shows that the faulting does not always control topography.

2. *The central part.*—From Canal Flats to Bull River the trench does not follow structural lines, neither in regard to the strike of the bordering formations, which is roughly parallel on both sides, nor, so far as could be found, in regard to the faults. The conclusion to be drawn from this point is that this part of the trench was developed by a stream flowing on an old erosion surface which was flat enough to allow the river to develop its course independently of structure.

This conclusion is strengthened by several factors. To begin with, the Purcell Range is thought by Schofield[1] to have been deformed in the Jurassic and peneplained in the Cretaceous, and at this time to have developed many valleys out of accord with the structure developed in the Jurassic mountain-building. After the

[1] S. J. Schofield, *Geol. Surv. Can. Mem. 76*, pp. 101–2.

uplift of the Purcell Range, these streams maintained their courses and developed antecedent drainage. That the old Purcell Range existed on both sides of the trench in this zone is evidenced by finding the typical Purcell strike on the east as well as on the west side of the trench. Also the Purcell series (pre-Cambrian) is present on both sides of the trench in this zone.[1]

The great width of this portion of the valley, 16 miles, is out of accord with the rest of the trench, which might be explained by greater age. Also there was found a continuation of the antecedent portion of the trench up into the Purcells leaving the trench in the vicinity of Cranbrook, and it is just south of here that the trench is found to be again connected with structure.

3. *The southern part.*—The southern structural unit extends from Bull River down to Gateway. In this zone there is a thrust fault on the east side of the trench which causes the Mississippian, or in some cases the Devonian, to be brought into contact with the Galton series, partly Cambrian and partly pre-Cambrian,[2] on the east. Large disconformities in this general region make it difficult to estimate the displacement of the fault. It probably is not more than 2,000 or 3,000 feet north of Elko, but at the boundary line it was estimated by Daly[3] to be as much as 10,000 feet. Ten miles south of Bull River it virtually dies out. Here the Devonian limestone comes down from the mountains into contact with the Mississippian in the valley.

This fault, which appears to limit the east side of the trench from Bull River to Gateway, was considered to be a normal fault by both Daly[4] and Schofield.[5] The writer has no definite proof that this is not the case, but there are several facts which suggest that it is a thrust fault. In the first place the trace of the fault plane at Gateway was followed with considerable certainty for several miles, and it was found that the fault plane curved decidedly up a tributary valley to the east (Fig. 7). This, of course, suggests an east-

[1] S. J. Schofield, "The Origin of the Rocky Mountain Trench," *Trans. Roy. Soc. Can.* (1920). P. 76.

[2] S. J. Schofield, *Science*, Vol. LIV, p. 666.

[3] R. A. Daly, *Geol. Surv. Can. Mem. 38*, p. 118.

[4] *Ibid.*

[5] S. J. Schofield, "The Origin of the Rocky Mountain Trench," *Trans. Roy. Soc. Can.* (1920), p. 76.

dipping fault plane. As the upthrow is on the east, the relation is that of a thrust fault.

Also along the eastern wall south of Bull River there is a place where the Mississippian appears to dip under the Galton series on the east. The common occurrence of the east-dipping thrust faults in the northern zone on the east side of the trench suggests the probability of this fault being one of the thrust type. It was thought by Dawson[1] that the fault continued north of Bull River because of a depression along the east side of the valley. The

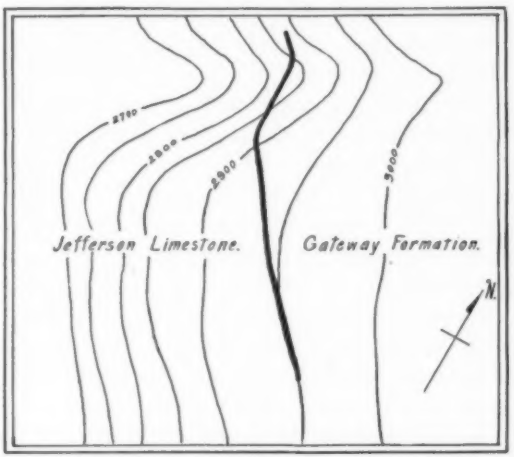

FIG. 7.—Sketch contour map showing trace of fault east of Gateway

writer considers that this depression is one of many instances of drainage along the flanks of the retreating valley glaciers. The valley in this southern section was probably originally defined by this fault plane, and subsequent erosion has broadened the valley chiefly to the west.

In conclusion, the Rocky Mountain trench does not appear to be the unit in its development and structure that it has been thought to be by Daly and Schofield. It appears instead to have been produced partly by normal erosion, partly by erosion along lines of structural weakness, and partly by the escarpment of a fault. Even in this last instance the faulting is probably of the thrust rather than of the normal type.

[1] G. M. Dawson, *Geol. Surv. Can., Ann. Rept.* (1885), p. 190 B.

ASPECTS OF ONTOGENY IN THE STUDY OF AMMONITE EVOLUTION

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It is well known that the development of an individual generally recapitulates to some extent the stages passed through during the evolution of its ancestors, or in other words, that "ontogeny repeats phylogeny." In the paleontological work of the last quarter of a century this principle of recapitulation has frequently been used in determining the relationships of fossils, and its general truth has been demonstrated among many groups of Invertebrates; for example, by Mr. R. G. Carruthers and others among the Rugose corals,[1] by Professor Grabau among the Gastropods,[2] and by numerous workers, particularly Mr. S. S. Buckman, among the Ammonites.[3]

That ontogeny is not always merely a recapitulation of phylogeny, however, has been recognized by zoölogists for many years; the development is often modified to fit the embryo for a special mode of life, as in many modern Arthropods, so that ancestral stages are obscured to a greater or less extent. In other cases on account of the individual hurrying through its development in order to attain maturity as early as possible, certain phylogenetic stages are "skipped" in development.

Numerous paleontologists have recognized the importance of this skipping of stages in development; Mr. S. S. Buckman dealt with it some years ago and has pointed out several examples.[4]

[1] See, for instance, R. G. Carruthers, "The Evolution of *Zaphrensis delansuei*," *Quart. Jour. Geol. Soc.*, Vol. LXVI (1910), p. 523.

[2] A. W. Grabau, "Phylogeny of *Fusus* and Its Allies," *Smithsonian Misc. Coll.*, No. 1417 (1904), pl. xviii, fig. 2.

[3] See, for instance, "Yorkshire Type Ammonites." Introduction to Vol. I (1909–12).

[4] S. S. Buckman, "Monograph of the Inferior Oölite Ammonites," *Palaeont. Soc.*, p. 289.

More recently, he proposed to call it by the name of "saltative palingenesis";[1] Dr. W. D. Lang suggested the simpler term "lipogenesis"[2] but as this term may convey a wrong idea of the skipping of stages *in ontogeny*, Mr. Buckman has now proposed the term "lipopalingenesis."[3]

The study of fossil lineages affords a ready means of investigating the various ways in which the skipping of stages has been brought about. This is particularly true in the case of ammonites, among which it is comparatively easy to study the ontogeny of successive members of a lineage.

From such studies it appears that there are several slightly different ways in which phylogenetic stages come to be skipped in the development of later members of a series. The object in this article is to draw attention to some of these aspects of lipopalingenesis.

THE OMISSION OF EARLIER CHARACTERS

In many cases the characters omitted are those of the earliest ancestors, and the "skipping" means rather the omission of the earliest phylogenetic stages. This occurs as a direct result of the acceleration of development (tachygenesis). A simple example may be found in the evolution of the Ammonoids or Nautiloids. It is generally accepted that these have evolved from straight *Orthoceras*-like forms, through curved *Cyrtoceras*-like forms, to closely coiled forms like *Nautilus* itself. Now it may be admitted that the *Orthoceras*-like stage is repeated in an abbreviated manner, in the early portion of the *Cyrtoceras* form, but in succeeding members of the series this stage becomes progressively shorter, and in Mesozoic Ammonites it can scarcely be said to be represented at all.

In most cases of lipopalingenesis the stage or character omitted is not the most primitive.[4] This is illustrated by the skipping of

[1] S. S. Buckman, "Yorkshire Type Ammonites," Vol. I (1909–12).

[2] W. D. Lang, *Proc. Geol. Assoc.*, Vol. XXX (1919), p. 60.

[3] S. S. Buckman, "Type Ammonites," Vol. III (1920), p. 11.

[4] It should be noted that in the case just given, the skipping of the *Orthoceras* stage merely represents the skipping of the earliest *skeletal* stage.

certain ornament stages in the development of Ammonites. The normal order of appearance of ornamentation in Ammonites, as in many other groups is (*a*) striae, (*b*) costae, (*c*) tubercles. But although this order is followed in phylogeny almost invariably, and often, in a general way, in ontogeny, in certain "accelerated" members of phylogenetic series the striate and occasionally also the costate stages are omitted in development, the tuberculate stage having been accelerated so that it directly succeeds the smooth stage. The smooth embryonic stage of an Ammonite may be restricted to the first few whorls, but however accelerated the specimen, the inner whorls appear to be always smooth; the smooth stage is never skipped, while the later costate or striate stages may be.[1]

Similar examples may be found among the Brachiopods and Lamellibranchs. Dr. Lang points out to me that in certain advanced corals twelve septa appear simultaneously in the embryo, the early phylogenetic stages, with fewer septa, being skipped.[2]

THE OMISSION OF COMPARATIVELY LATE CHARACTERS

A more interesting form of lipopalingenesis is illustrated by certain Ammonite groups; perhaps the clearest example is to be found in the evolution of the Liparoceratidae.[3] Slender "capricorn" Ammonites of this family evolve through intermediate stages to stout bituberculate forms, but the ontogeny of the latter shows no stage in any way comparable with their immediate ancestors, the slender capricorn forms. This skipping of the slender-whorled stage is represented diagrammatically in Figure 1, which shows sections of three Ammonites typical of (*A*) the slender capricorn forms, (*B*) the intermediate forms, (*C*) the stout forms, from one genetic series. In the ontogeny of the capricorn form the depressed early whorls (i and ii) pass into round whorls (iii–v); in (*B*) the stage with depressed whorls is shortened (by acceleration of the slender whorl stage) but the latest whorls are stouter than in the adult of *A*. This stout form of whorl is more characteristic of *C*, and has

[1] In certain accelerated Gastropods striae may be present on the protoconch and the smooth stage is there omitted (Grabau, *op. cit.*).

[2] See *Geological Magazine*, N.S., Dec. V, Vol. IX (1912), p. 557.

[3] A. E. Trueman, "The Evolution of the Liparoceratidae," *Quart. Jour. Geol. Soc.*, Vol. LXXIV (1919), pp. 2, 7.

been accelerated; since the depressed *early* whorls are also prolonged the slender whorl stage is skipped entirely in the development of this form.

The reason for this skipping is perhaps best appreciated when it is remembered that the Ammonite *C* was thus able to produce the adult form directly, instead of developing from stout (embryo) to slender (youth) and back to stout (adult). The tendency to omit in development the stage which appears unnecessary for the production of the adult form would perhaps be expected; the most interesting fact is that this skipping is accomplished not simply by the acceleration of the stout form of whorl but partly by an *apparent* retardation of the early characters, notwithstanding that the series is distinctly progressive.

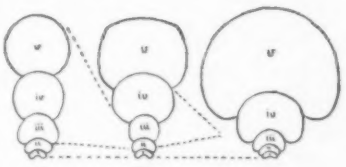

FIG. 1.—Sections to show the changes of whorl-shape in three ammonites from a single lineage of the Family Liparoceratidae:

A, a slender capricorn ammonite.

C, an involute stout ammonite.

B, a form intermediate between these two.

Without discussing here the biological interest of these observations, it is perhaps not out of place to notice that if lipopalingenesis is of frequent occurrence, the tracing of phylogeny from ontogenetic evidence is not so easy as has been thought by some workers. It is comparatively easy to follow cases of skipping of stages when an early phylogenetic stage is omitted, but in cases like the one just described, where the characters omitted are some of the more advanced, there is obviously much difficulty in tracing descent from developmental evidence alone. In such cases, descent can only be proved by the finding of series of intermediate forms connecting the various species.

A NEW PHYTOSAUR FROM THE TRIAS OF ARIZONA

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Among the vertebrate remains from the Triassic of the western states no other group is so abundantly represented as the Phytosauria. Relatively abundant as fossils of this group are, however, there is much to be learned of each of the several distinct types that have been described. For the most part it is the skull that is available for study, but even this is imperfectly known.

Some time ago the writer described a well-preserved phytosaur skull from Arizona, now in the geological museum of the University of Wisconsin. This skull was considered a new form and was made the type of the genus *Machaeroprosopus*.[1] While several of the doubtful details of the phytosaurian skull were made known by the study of the specimen, especially the relations of the bones of the posterior side, the palate, as is usually the case, was left in doubt.

Through the kindness of the University of Chicago the writer was permitted some time ago to study a phytosaur skull in the collections of Walker Museum; a skull very similar to the University of Wisconsin specimen in many points. The study of this material has made evident several pointed suggestions especially concerning the structure of the palate.

The specimen herein described is No. 396 of the Walker Museum Vertebrate Paleontology Collections. It is the gift of Professor J. E. Anderson, formerly of the School of Mines, at Socorro New, Mexico. The name of the collector is unknown and the exact locality has not been recorded. However, the skull is known to

[1] M. G. Mehl, "New or Little-known Reptiles from the Trias of Arizona and New Mexico, with Notes on the Fossil-Bearing Horizons near Wingate, New Mexico," *Bull. University of Oklahoma*, New Series No. 103, University Studies Series No. 5, 1916, pp. 5–24.

have come from the Triassic of Guadaloupe County, near Santa Rosa, New Mexico.

The material collected consists of a few large, well-preserved pieces of bone representing a fairly complete skull (Fig. 1). In the skilful hands of Paul C. Miller the missing portions have been restored in plaster and the major features are almost as certainly determined as though all the fragments had been collected. On both the dorsal and the ventral sides the skull is complete along the median line save for the occipital condyle proper. On the right side the jugal, except for the portion that forms the posterior border of the antorbital fenestra and the process that takes part in the border of the orbit, is missing, as is the quadratojugal, the squamosal, and all but the anterior end of the postorbital. On this side, too, the outer end of the paroccipital and the quadratopterygoid bar are missing. On the left side the missing portions are much the same as on the right, except that the restoration extends farther forward. On the left side the posterior end of the jugal and all of the quadratojugal are preserved.

The skull (Fig. 1) is large, about 865 mm. long, and massive. It is a crested form of the "broken outline" type. From an oval cross-

FIG. 1.—*Machaeroprosopus andersoni*, side view of restored skull, slightly over one-sixth natural size. Sutures indicated by broken lines cannot be determined.

section just behind the expanded and abruptly downturned tip, the rostrum gradually assumes an A-shaped cross-section. Back from the tip for a distance of about 293 mm. the rostrum does not increase in depth materially. At this point, however, the outline of the crest bends in a pronounced curve upward for a short distance and then extends in an essentially straight line up to the anterior border of the nares, 512 mm. from the tip of the rostrum. As the crest approaches the nares after the abrupt rise, it loses much of its angular cross-section.

The narial "hump," while actually rising above the plane of the cranium proper about half an inch and while somewhat accentuated by the depression of the cranial roof in front of the orbits, is not so conspicuous as in several other forms. This is due to the fact that the crest is but slightly depressed immediately in front of the nares.

OPENINGS OF THE SKULL

The position of the *nares* is that of the most highly specialized phytosaurs, high on the skull and not far from the eyes. The posterior border of the nares is about 105 mm. in front of the center of the orbit. The openings are 63 mm. long and about 21 mm. wide. They are separated by a moderately thin partition that does not reach the level of the outer borders. The plane of the combined openings is directed upward.

The *orbits* are slightly longer than wide, about 62 mm. in diameter.

The *antorbital fenestrae* are somewhat distorted. They appear to have been about 104 mm. long and perhaps 45 mm. wide. While they do not extend forward beyond the nares, as is the case in similar forms, this is due to the moderate length of the antorbital fenestrae and not to a unique position.

The sides of the *lateral temporal fenestrae* are restored in part. Because of this and some distortion it is not possible to give exact dimensions. It is thought, however, that the greatest diameter was not over 120 mm.

The *supratemporal fenestrae* show a development similar to that of *Mystriosuchus*.[1] The posterior border, i.e., the parieto-

[1] J. H. McGregor, "The Phytosauria, with Especial Reference to *Mystriosuchus* and *Rhutidodon*," *Mem. Am. Mus. Nat. Hist.*, Vol. IX (1906), Part II.

supramosal arcade is markedly depressed. The depression of this arcade has not advanced so far as in *Machaeroprosopus validus*.[1] The opening is very inconspicuous in a superior view because of the backward extension of the postorbital. The opening is directed out and back. It is slitlike, but its length cannot be determined because the outer posterior border is missing.

SEPARATE BONES OF THE DORSAL ASPECT

The *premaxillae* are gradually expanded laterally at the anterior ends for the accommodation of the large terminal teeth. The expanded portion is abruptly down-curved and extends about 30 mm. below the palate surface of the rostrum. At the margins of jaw, the premaxillae unite with the maxillae at about the twenty-fifth tooth. From this point the suture extends back and up in an irregular line. At the median line each premaxilla sends back a process to within 45 mm. of the nares. This process and a lateral posterior process extending back the same direction clasp the anterior process of the septomaxilla.

The *septomaxillae* are larger than in any other form that the writer has examined. They are united along the median line for a distance of 48 mm. and thence extend forward between the posterior process of the premaxillae a distance of 45 mm. The septomaxillae form a large area about the front and sides of the narial prominence, but their exact posterior extent cannot be determined. It is thought that they make up but a small part of the narial septum.

The *maxilla* has its greatest anteroposterior extent along the alveolar margin. In this respect it differs from the University of Wisconsin specimen referred to above.

The *nasals* form the posterior, median, and most of the lateral border of the nares. The lower anterior margin extends some distance beyond these openings, essentially as far as the septomaxillae. Posteriorly they extend about 35 mm. beyond the posterior border of the antorbital vacuity.

In the shape and extent of the *lachrymals* and *prefrontals* there is the normal phytosaur development.

The *parietals* differ from those of *Machaeroprosopus validus*[2] in

[1] Mehl, *op. cit.*, p. 8, Fig. 2.

[2] *Ibid.* p. 11.

that their combined width is equal to the interorbital width. Their length is 67 mm. and combined width the same.

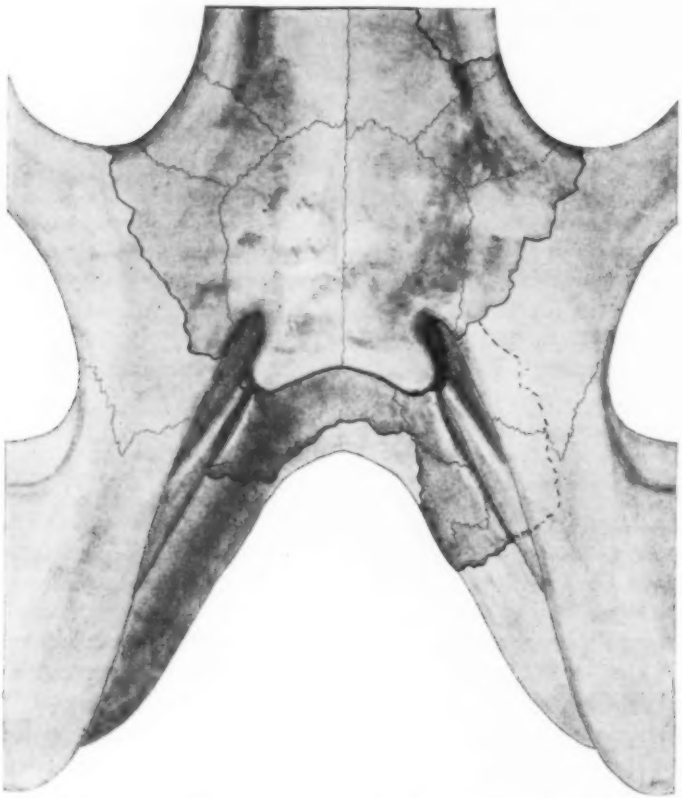

FIG. 2.—*Machacroprosopus andersoni*, details of the posterior end of the skull as seen from above. Restored portions are indicated by lighter shading and less heavy outlines. Two-thirds natural size.

The *postfrontals* are small and make but a small part of the orbit boundary, as is usually the case.

The relation of the *postorbitals* is not clearly shown. The posterior extent of these bones cannot be determined, for that portion of the skull is restored.

The *jugals* form the lower posterior border of the antorbital vacuity, the lower anterior border of the lower temporal vacuity, and enter slightly in the boundary of the orbit. Along the lower border of the skull their posterior extent is such as to practically exclude the *quadratojugal* from that margin.

Little or nothing can be said of the squamosal development.

POSTERIOR VIEW OF THE SKULL

So much of the skull as seen from the posterior side is restored that little of value can be given in description. The skull has been telescoped downward, but it is evident that it was considerably wider than high. In so many details is the skull like the type of *Machaeroprosopus validus* that it is assumed the similarity extends to the posterior side. Some of the differences in the development of the region about the supratemporal open-

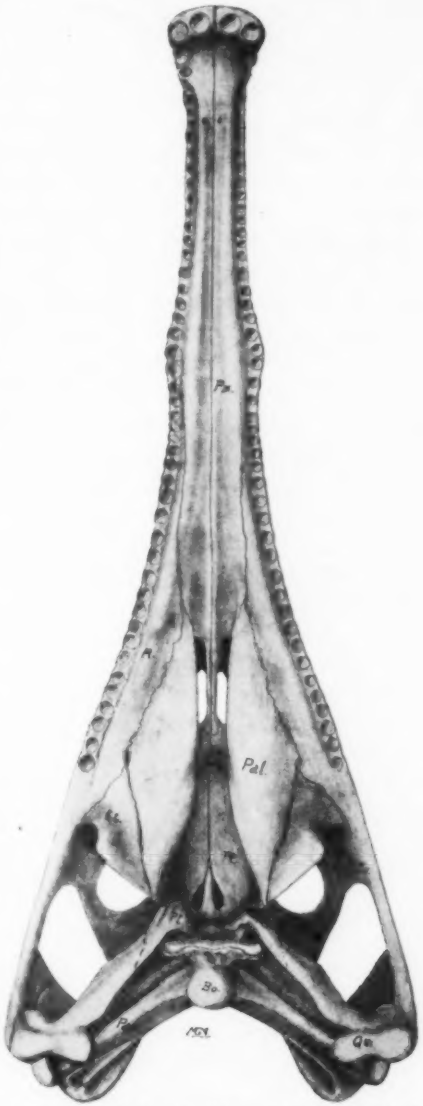

FIG. 3.—*Machaeroprosopus andersoni*, restored palate surface, slightly over one-sixth natural size.

ings are evident in a comparison of Figure 2 with that of *M. validus*.[1]

THE PALATE

The palate of this specimen (Fig. 3) seems very little distorted, but although the configuration of the bones is readily determined, some of the sutures are obscure. The bones are thin and overlapping, and the slightest abrasion tends to obliterate the unions.

The palate is marked by the characteristic phytosaurian ridges just within the alveolar border. These start indistinctly near the third tooth back of the down-turned terminus of the rostrum and increase in prominence to a point a little in advance of the internal nares. From here they flatten out posteriorly and lose their identity before the last tooth is reached. A slight median ridge, low and rounded, continues forward from the internal nares to about mid-length of the rostrum.

In the region of the twenty-third tooth, there is a conspicuous lateral expansion or swelling of the rostrum. The alveolar ridges broaden in this region to fill in the increased width.

Among the most striking features of the palate is the development of the narial arch. In *Angistorhinus*,[2] from the slight arching formed by the alveolar ridges far forward, the height increases gradually until it is broad and marked just in front of the nares. Here the height increases rapidly to about 42 mm. at the posterior end of the nares. At this point the arch has a width of 82 mm. In this genus there is not the slightest suggestion of the constriction of the arch at the lower palate plane, the suggestion of a primitive false palate.

In *Mystriosuchus*, as McGregor has shown,[3] the constriction of the narial arch at the lower palate plane is marked. To quote:

> This arched condition of the palate suggests two questions of great importance in their bearing upon the genetic relationships of the group, namely: (1) Do the Phytosauria exhibit the incipient formation of a secondary palate? and (2) if so, is this the first step in a phyletic series, culminating in the highly

[1] Mehl, *op. cit.*, p. 8, Fig. 2.

[2] M. G. Mehl, "The Phytosauria of the Trias," *Jour. Geol.*, Vol. XXIII (1915), No. 2, pp. 129–65.

[3] McGregor, *op. cit.*, pp. 42–43.

modified palate of the eusuchian crocodiles? As for the first of these questions I feel that there is no escape from an affirmative answer; an examination of the palate of either *Mystriosuchus* or *Phytosaurus* [*Lophoprosopus*] shows a pair of longitudinal palatine ridges . . . . which plainly represent the beginnings of a secondary palate. . . . .

The rounded inner border [of the portion of the palatine about the base of the narial vault] projects very slightly toward the middle line, so that the palatal aspect of the cranium exhibits two elongate ridges which approximate each other within 25 mm. at the level of the anterior border of the nares, diverging gradually behind this region. These palatine ridges partly obscure the outer part of the narial cavities and are continued anteriorly on the maxillaries, but fade out posteriorly without involving the pterygoid. . . . . It should be explained that these ridges do not present a sharp edge, but are broadly rounded. Nevertheless it is an approximation of the palatines, ventral to the internal nares and the pterygoids, and it seems to me that it must be interpreted as a *tendency* toward the formation of a secondary palate. . . . .

In the present form this tendency is so marked that there can be no doubt as to its meaning. The narial vault has its greatest width somewhat back of the nares. The cavity is still partly filled with matrix, but is at least 80-90 mm. wide and somewhat over 50 mm. high. So restricted is the arch at the lower palate plane by the median extension of the palatines, that the opening as seen in a palate view is little more than a slit, not over 24 mm. wide near the posterior border of the nares and gradually widening to the region of the interpterygoid vacuities. This constriction in the narial region is in the form of sharp-edged, thin, horizontal plates extending beneath the narial vault at the plane of the palate. The suggestion of an unfinished or rough edge bespeaks a cartilaginous or fleshy continuation. It is believed that the air passage was thus completely closed below for a considerable distance back of the nares.

The alveolar ridges cannot be considered as part of this "false palate," as is suggested by the foregoing quotation. In the present form they are quite distinct from the palatine extensions beneath the nasal vault. These alveolar ridges, always conspicuously developed in the phytosaurs, should probably be looked upon as buffers to prevent the breaking or interlocking of the teeth through the sharp snapping of the jaws in an unsuccessful attempt at seizing prey.

OPENINGS OF THE PALATE

The length of the *internal nares* is 71 mm., about 8 mm. greater than that of the external openings. The internal nares are about 20 mm. in advance of the externals at their posterior border.

The *postpalatine foraminae* are exceptionally small and inconspicuous. They are, in fact, little more than slight depressions or cracks along the palatine-ectopterygoid union. They are not over 30 mm. long and if actually perforating the palate are not more than 3 mm. wide.

The *interpterygoid openings* are exceptionally small. Their exact anteroposterior extent cannot be determined, but they could have been but little more than 25 mm. long.

THE BONES OF THE PALATE

Some of the details of the relations of the bones of the palate are not at all certain. In the palate restoration, the writer has attempted to show the relation as the weight of the evidence seems to indicate and not as indisputably determined.

The *premaxillae* apparently have a remarkable posterior extent on the palate surface. They seem to form the anterior border and the entire inner boundary of the internal nares and extend a short distance back of these openings along the median line. An unpublished drawing of this specimen by S. W. Williston doubtfully places the posterior end of the premaxillae about 40 mm. in front of the internal nares. The bone in this region is platey and brittle and has been somewhat abraded in preparation. The writer recognizes the possibility of the premaxilla-vomer suture in this region, but cannot verify this point.

The *maxillae* extend forward on the palate surface to the twenty-fourth tooth, numbering from the front. Their width on the palate is at no place much greater than that required for the alveolar ridges. The union with the jugal as seen in a palate is not determinable.

The *vomers* seem to be exceptionally small and confined to the posterior and possibly the posterolateral borders of the internal nares. This is a condition decidedly unlike that usually attributed to the phytosaurs and is merely suggested. What is assumed to be

the union of the premaxillae and the vomer at the inner posterior border of the nares may be a fracture. If so it is remarkable for its symmetry in relation to the median line of the skull. Of the posterior boundary there can be little doubt. It joins the pterygoid in a forward convex line about 32 mm. back of the internal nares.

The *palatines* apparently form a goodly portion of the lateral borders of the internal nares. Aside from this, however, they seem to be largely confined to the lower palate plane. It is thought that their union with the pterygoids and vomers is at or near the base of the narial vault, but of this one cannot be sure because of the matrix-filling part of the cavity. Posteriorly the palatines come to an acute angle, the point of which prevents the articulation of the pterygoids with the ectopterygoids on the palate surface.

The *ectopterygoids* are small, triangular bones. The posterior borders are down-curled so as to be conspicuous in a lateral view of the skull.

The *pterygoids* are exceptionally large, but are almost entirely confined to the sides and roof of the narial arch. Their extent along the pterygo-quadrate bar cannot be determined.

The *parasphenoid* has been destroyed, but it must have been very similar to that shown in the palate restoration. The union between the *basi-sphenoid* and the *pterygoids* and *basi-occipital* is as indicated in the restoration. The relation of the other bones of the posterior part of the skull as seen in the palate view cannot be determined. The relations shown are those determined from the University of Wisconsin specimen mentioned above.

THE TEETH

With the exception of a few roots and one partially erupted tooth in the middle of the series that shows the crown, all the teeth have been lost. The alveolar margin of the jaw is splendidly preserved for the most part and gives a good indication of the number of the teeth and of their variations in size.

The alveolae are all distinct and usually separated by a space of at least 3 to 5 mm. In each maxilla there are apparently twenty-four teeth and twenty-three in each maxilla, a total of ninety-four

in the upper dentition. In the downward portion proper of the premaxilla there are two alveolae of a size and shape to indicate long conical teeth of about 21 mm. diameter at the base. Immediately behind the down-turned portion is another large alveolus, about 15 mm. in diameter. This is followed closely by a fourth, considerably smaller, alveolus. Between the fourth and fifth alveolae is a conspicuous space. This is marked on one premaxilla by a depression as though for the reception of a tooth from the lower jaw. The following alveolae, with the exception of the last few on the premaxilla, increase gradually in size from about 6 mm. to 12 mm. There is a marked lateral expansion of the rostrum near the posterior end of the premaxillae for the accommodation of three or four exceptionally large teeth. The root of one of these is preserved and measures 13 mm. in diameter. The crown preserved in the maxilla series as mentioned above is laterally compressed with sharp, slightly serrate, anterior and posterior edges.

It would seem that the dentition was very much like that of *Machaeroprosopus validus*,[1] greatly enlarged seizing teeth in the front, grading through smaller, sharp, conical to laterally compressed slicing teeth behind. The space between the fourth and fifth alveolae indicates likewise a shorter jaw with large terminal teeth directed sidewise.

RELATIONSHIPS AND HABITS

Of the close affinity between the present specimen and that described as *Machaeroprosopus validus*[2] there can be no doubt; both skulls are crested forms of the "broken outline" type; both have the depressed posterior border of the supratemporal openings; and both have enlarged, conical terminal teeth with laterally compressed, sharp-edged, slicing teeth behind. The skulls differ in so many minor points, however, that they can scarcely be placed in the same species. The writer will designate the present form, therefore, as *Machaeroprosopus andersoni* in honor of Professor Anderson, who presented the material to the University of Chicago.

[1] Mehl, *Bull. Univ. of Oklahoma, op. cit.*, p. 20.

[2] *Ibid.*

The following table comparing the two forms will show the chief differences on which the new species is established.

Machaeroprosopus validus	*Machaeroprosopus andersoni*
Postero-median border of supratemporal fenestrae completely depressed.	Postero-median border of supratemporal fenestrae not completely depressed.
Anterior border of nares elevated above lateral borders.	Anterior border of nares not elevated.
Terminal expansion of rostrum abrupt.	Terminal expansion of rostrum gradual.
Nasals not extending to anterior border of nares.	Nasals extending some distance in front of anterior border of nares.
Greatest length of maxillae above alveolar margin.	Greatest length of maxillae at alveolar margin.
Approximately seventy-four teeth in upper dentition.	Approximately ninety-four teeth in upper dentition.
Six large teeth in terminal expansion of rostrum.	Four large teeth in terminal expansion of rostrum.
Alveolae crowded, occasionally confluent.	Alveolae not crowded.
No lateral expansion of rostrum at posterior end of premaxillae.	Lateral expansion of rostrum at posterior end of premaxillae.

The Phytosauria are a unified group in that they all tend to develop certain peculiarities that set them off from other groups in a striking manner. All developed the snoutlike elongation of the skull, an elongation that left the nares far from the tip. In some cases there seems to have been an actual retreat of the nares. There seems also to have been a tendency to elevate the nares above the plane of the cranium proper, a goal very conspicuously reached in several forms. All of the phytosaurs showed a more or less marked development of greatly enlarged terminal teeth and most of them developed at least a crude slicing dentition farther back in the jaws.

These modifications or tendencies are so distinctive that they have called forth considerable speculation as to the habits of the

phytosaurs. The seemingly common goal in the modifications of all the phytosaurs suggests similar habits. Of the probable habits of *Machaeroprosopus* the writer has stated in another place:[1]

> All of the phytosaurs were supposedly more or less amphibious in habit. Still, the heavy dermal armor of several of the forms would indicate that a very considerable part of their time was spent on the land. The posterior position of the nares is usually not considered a distinct aquatic adaptation in the case of the phytosaurs. It is rather explained, along with the long snout and large terminal teeth, by attributing to the slender rostrum the function of a prod or rake with which the possessor searched out worms and other soft bodied invertebrates, etc., in the mud of shallow waters while the nares, by virture of their position, were above the surface of the water.
>
> There is a marked tendency in most of the phytosaurs, a tendency in which *M. validus* surpasses all other known forms, for the nares to rise on a considerable prominence. This would seem to be a modification entirely uncalled for were the position of the nares due solely to the use of the rostrum as a prod. So situated are the nares in *M. validus* that it could submerge the body save for the narial hump and lie in wait admirably concealed from its enemies, or more likely, from its prey. Certainly the teeth of this form are more fitted for tearing large vertebrates than for small, mud-burrowing creatures. Then too, *Machaeroprosopus* could scarcely pick small objects from the ground because of the difference in length between the upper and lower jaws. When the jaws were closed the terminal teeth of the lower jaw were functionless and the upper terminal teeth were but little better. It was not until the jaws were wide open that the terminal teeth could be used effectively either as a rake or for seizing any sort of prey. With the jaws separated, however, the upper and lower terminal teeth were directly opposed and admirably fitted for seizing and tearing large animals. It seems likely that *M. validus* was wont to lie in wait concealed close up to the shore in shallow waters ready to seize its prey when the latter came down to drink. Once the prey was dragged into the water it was at the mercy of its captor, for the dentition of the latter probably matched that of any carnivorous land form of the time and the phytosaur had the distinct advantage of being entirely at ease in the water.

If these were the habits of the more highly specialized phytosaurs, and the assumption seems logical, the group was remarkably well adapted to the conditions of the times. The adaptation was, moreover, of a very peculiar nature. In most cases adaptations seem to do little more than tend to counteract adverse conditions. For instance, the development of speed in ambulatory forms of

[1] Mehl, *Bull. Univ. of Oklahoma, op. cit.*, pp. 23–24.

arid regions permits a wider range about the limiting water supply to compensate for the diminished food supply and the distance between water-holes.

In *Machaeroprosopus* the modifications not only met an emergency but actually turned it to advantage; the phytosaur waited for the rigorous conditions to bring his food within reach. If our interpretation of the conditions in the western interior of North America during Triassic times is correct the scarcity of food necessitated a wide range for many forms. This meant speedy forms ordinarily difficult of capture, but it also meant the periodic crowding of the limited water-holes; it compelled the food to walk to the captor.

It is not easy to see why a group so remarkably fitted to their environment as was the phytosaur group should not prosper better as a race. They were very short lived, confined to the latter part of the Trias, apparently. One can scarcely appeal to *overspecialization* unless this means "fitting in" rather than marked structural change. The phytosaurs were scarcely less generalized than the living crocodilians. Perhaps *perfection* alone is enough to condemn a race. A consideration of this possibility will form the basis for a future paper.

ADAPTING A SHORT-BELLOWS, ROLL-FILM KODAK FOR DETAIL WORK IN THE FIELD

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Most geologists, when in the field, have occasionally felt the need of a portable camera with which they might take large-size detail photographs. The ordinary equipment for such work, the long-draw, box camera, is far too heavy and bulky to be carried by the geologist as a part of his daily accoutrement. The roll-film kodak with the customary short bellows which is most convenient for his usual needs, fails when he wishes a picture larger than about one-tenth natural size, and the auxiliary portrait lens does not greatly increase the scope of his outfit. If he wishes a detail picture of a fossil in place, a curious marking or texture of a rock which cannot be conveniently sent to his headquarters, he must note the place and come again later with the more bulky equipment. He almost never does.

The device described below has been found by the writer to be a simple and convenient solution of the problem. An auxiliary portrait lens was first secured to fit the kodak he wished to use. This attachment consists of a simple plano-convex lens of about 52-inch focus. When placed close in front of the kodak lens this causes parallel beams of light to become slightly convergent when they strike the main lens system and thus shortens the focus of the combination (See Fig. 1, Scale II). With the principal focus now somewhat nearer the ground glass, the slight additional excess of bellows-length permits focusing on closer objects and hence larger pictures than with the kodak lens only.

Next, there were procured from an optician two more lenses of foci approximately 16 inches and 8 inches respectively. These were ground to the proper diameter to fit the cell belonging to the original auxiliary. The three lenses are readily interchangeable by unscrewing the ring which holds in place the lens used. By using

the two additional lenses, one at a time, the focus of the combination is further reduced, as shown in Scales III and IV of Figure 1. With the three used successively, the entire range of object-distance from infinity to less than eight inches can be accommodated, using only the two inches adjacent to the bellows-limit for adjustment.

After obtaining the lenses, the several combinations were calibrated for different distances by focusing on a ground glass placed in the image-plane and the readings made on a white celluloid metric

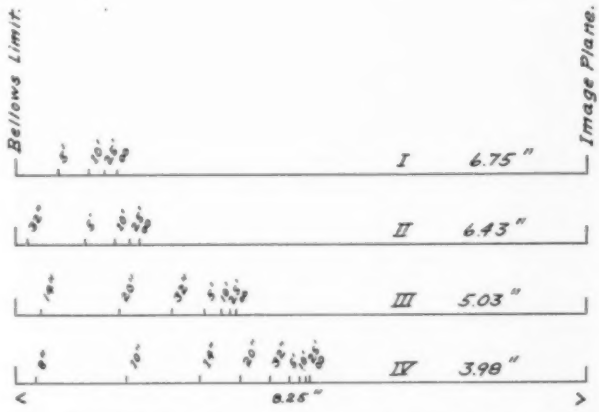

FIG. 1.—Diagram showing four focusing scales in relation to the image-plane and bellows-limit as follows: Scale I, with kodak lens of 6.75-inch focus; Scale II, using 52-inch focus auxiliary lens; Scale III, using 16-inch focus auxiliary lens; Scale IV, using 8-inch focus auxiliary lens. The figures at the right show the foci of the several combinations and the diagram shows clearly the increase in scope of the bellows as the auxiliaries of shorter focus are added.

scale which was attached to the bed, as shown in Figure 2. From these data were constructed the tables I and II which were photo-reduced and pasted in place on the bed of the kodak as shown. Here they are out of the way, but always convenient. Table I shows the setting on the metric scale for different object-distances, the three parts of the table referring, respectively, to the three auxiliary lenses, I, II, and III. Table II gives the object-distances for different ratios of object to image. For example, suppose one

wishes a picture which is one-half natural size. In Table II opposite the ratio 2 is given the object-distance 15 inches. Then in Table I, interpolating between 14 inches and 15 inches, we find that the focus should be at the scale-reading of 10.85 and that auxiliary lens II should be used. The kodak is then set with the lens 15 inches from the object to be photographed. Table II gives also at the bottom the foci of the three combinations, the focus of the kodak lens alone being about 6.75 inches.

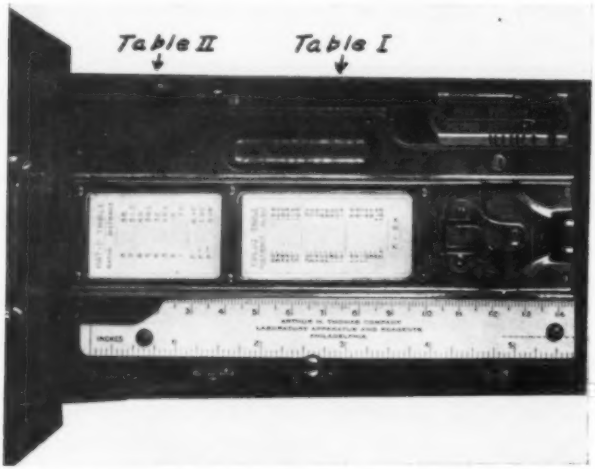

FIG. 2.—Photograph of bed of kodak showing attached metric scale and two tables as described in the text. (Somewhat reduced.)

The celluloid scale may, if desired, be so set as to read inches of focus from the ground glass directly; that shown was set arbitrarily and the readings indicate position only. With this device, sharp and undistorted photographs up to natural size may be taken by using a tripod or one of the numerous types of clamp support, and an aperture of F/32 or smaller. Since in pictures of this kind where the object is not plane, it is almost always necessary to reduce the aperture and give a time exposure in order to get depth of focus, there is no additional difficulty due to the auxiliary lens. Instantaneous pictures at full aperture may be made if need be, but the

distance must be estimated with considerable accuracy to secure good definition. Such rapid exposures are rarely necessary or even desirable in the case of geologic subjects.

Anyone desiring to use this device will find that auxiliary lenses of 52-inch, 16-inch, and 8-inch foci will be a suitable series for a 3A kodak having a lens of about 6.75-inch focus. For the use of others with different kodaks, the following formula is given:

$$\frac{1}{F_{o+1}} = \left(\frac{1}{F_o} + \frac{1}{F_1}\right) 1.08$$

where F_o = focus of kodak lens, F_1 = focus of auxiliary lens, and F_{o+1} = focus of the combination. This formula is only approximate but is sufficiently accurate to guide one in the selection of a series of auxiliary lenses. These lenses can be secured from any well-equipped optician who does his own grinding. They should then be calibrated by focusing on a ground glass in the image-plane and taking readings on the scale. Tables can then be constructed, as shown in Figure 2.

The extra lenses can be carried in any convenient pill-box. The cost for the three lenses and cell is less than five dollars and the outfit has been found by the writer during two seasons' field work to give highly satisfactory results.

SEGREGATION GRANITES

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The deposits of asbestus of the Eastern Townships in Canada are the most exploited of the world. In 1919 $18,000,000 worth or 3,082,384 tons were mined. This means a great deal of development and has given J. W. Dresser, the geologist who has for years followed the region with the closest attention, a chance to make observations which are of general theoretical interest. Fifteen years ago[1] Dresser suggested that certain granites seemed to have been differentiated from the same magma from which were derived the serpentines in which the veins of asbestus chrysotile occur. This would tend to support Daly's idea[2] that granite is a product of differentiation from a basaltic substratum, *but not necessarily that it is "syntectic,"* that is, due to previous assimilation of something like a quartzite.

Some twenty years ago I had occasion to study with critical care what I then called "acid interstices" which practically always occurred near the middle of every diabase dike of over ten meters thickness or so.[3] I had over two hundred thin sections, and while Bayley and Irving and Wadsworth were inclined to believe the interstices filled with micropegmatite were secondary, I was inclined to agree with A. C. Lawson in believing them primary. By a careful study I convinced myself that such was the case. Later studies showed that the filling of similar interstices in effusive rocks was characteristically different, and I called the effusive texture doleritic. The conception I gathered was that these

[1] See *Bull. Geol. Soc. Am.*, Vol. XVII, p. 510; also *Canadian Survey Memoir*, Vol. XXII, and other papers by Dresser given in Ferrier's finding list.

[2] *Igneous Rocks and Their Origin*, p. 361.

[3] *Geological Survey of Michigan*, Vol. VI (1899), pp. 235–42, the work was largely done in 1890; see *Report of the State Board of Geological Survey of Michigan for the Years 1891 and 1892*, p. 177.

cavities were "filled with the residuum of the molten magma. Enough of the rock was formed to make it perfectly solid, for no further motion could take place without disturbing the micropegmatite borders of the felspar laths and fracturing the excessively delicate apatite needles. The remaining interstices seem, agreeing with the general law of increasing acidity in residual magmas, to have been filled with the final concentration of an acid aqueo-igneous magma which had been corroding the olivine and forming the less basic augite from it. In this magma were also concentrated the absorbed gases, aqueous and otherwise, which the dike margin originally contained and which, as the dike solidified at the margin, would probably be driven from it and concentrated at the center.

"The acid magma thus left seems to have proceeded to produce brown hornblende upon and out of the augite; brown mica upon and out of the iron oxides, as Smyth has suggested; and pegmatite growths on or out of the feldspar, while apatite needles formed across the cavities." The convincing arguments were that these interstices did not occur in marginal sections, and showed no signs of being more abundant in uralitic sections, but were best developed in otherwise fresh dikes, and were not present with superficial textures such as the amygdaloid textures.

The facts I have seen in the Medford diabase and elsewhere in the intervening thirty years have only strengthened the conviction that this interpretation is substantially correct, though it should be expressed not so much in terms of acid and basic, as in terms of those eutectic lines and troughs which the geophysical laboratory at Washington has worked out, the theoretical bearing of which has been developed by N. L. Bowen.[1]

The fluid magma from which the minerals of these interstices crystallized out would be closely held by capillarity if they were not large. But with increasing coarseness and size of interstices there would be more chance for it to drain out like honey from the honeycomb, or as Bowen and Harker have suggested, be squeezed

[1] "The Problem of the Anorthosites," *Jour. Geol.*, Vol. XXVIII (1919), pp. 393–434; *ibid.*, Vol. XXV, 3 (1917), pp. 210–44, "Crystallization—Differentiation in Igneous Magmas," and literature there cited; *Am. Jour. Sci.* (1915), p. 407; (1914), p. 207, etc.

out like fluid from a filter press. When this happens we have the aplitic red rock associated with the Duluth Gabbro described most fully and lately by F. F. Grout[1] or with that of Mount Bohemia, so fully described by F. E. Wright.[2] If one supposes this segregation conducted on a still larger scale or so that the crystallization shall be somewhat coarser and the grain coarser, the logical outcome would be a granite. This is just what Dresser finds that the advance of mining operations has conclusively proved[3] by showing that masses of granite have no separate connection with the earth's interior.

The largest mass of differentiated hornblende granite mentioned by Dresser is three-quarters of a mile long by one-quarter of a mile wide, with a coarser pegmatite border two or three feet wide and a porphyritic texture throughout. This granite "is an indication rather than a cause" of the presence of acid waters in the magmatic residue needed to produce serpentine and asbestos. It is interesting to note that Bowen starting with peridotite as a monomineralic differentiate suggested that the region "may" furnish a "complementary granitic differentiate." He is apparently right!

Now the laws of physics and chemistry are universal. If this has happened in the Lake Superior region and the Eastern Townships it must have happened in many other places. One is tempted to consider the Mull pitchstones[4] the "leidleites and inninmorites" which (*a*) apparently occur only as intrusions, (*b*) are high in primary water, (*c*) are glassy at the center and stony at the sides, i.e., coarser at the margins, as representing such a magma as that of the red rock of Wright, of Grout, etc., chilled more quickly and without loss of water, but yet like many aplites or the granite described by Dresser, consolidating more slowly at the margin. This I have shown is more likely to happen when the initial magma tem-

[1] "A Type of Igneous Differentiation," *Jour. Geol.*, Vol. XXVI (1918), p. 618.

[2] *Report Michigan Geological Survey* (1908), p. 387.

[3] "Granitic-Segregations in the Serpentine Series of Quebec," *Transactions of the Royal Society of Canada* (1920), pp. 7–13. Compare also N. L. Bowen, "Differentiation by Deformation," *Proc. Nat. Acad. Sci.* (1920), p. 160.

[4] E. M. Anderson, and E. G. Bailey, *Quart. Jour. Geol. Soc.*, Vol. LXXI (1916), pp. 205–16, London.

perature is low. In other words they are "secundine"[1] to the great series of basalts and gabbros.

The primary water-content (exceeding the average for rocks of similar composition) which Anderson and Bailey emphasize as characteristic is very suggestive. The analysis (1) of the glassy part of the leidleite may be very nearly that of the anchieutectic solution that once filled the acid interstices and that wandering off by itself would make red rocks and even hornblende granites. That though central it is glassy may be due partly to great viscosity and less power of crystallization, due to less lime, iron, and magnesia, and more silica, partly to a more rapid passage through the crystallization range of temperature, even though later.

If we study these analyses (see following table), 1 and 2 given by Anderson and Radley, and compare with 3 and 4, Bowen's analyses of Canada diabase and dike granite and with the average igneous rock as given by Clarke and Daly we find, (1) that they are not very far from the average igneous rock, (2) that they are not very far from the eutectic trough or line to which I called attention in 1904,[2] (3) that they are not very far from the analyses of the red rocks given by Grout and Wright, etc., (4) that the

[1] I have found the following classification of dikes with the appropriate adjectives to have some value:

1. *Invasive.*—Forced more or less slowly into cavities formed by the extra hydrostatic pressure of the invading magma; contacts irregular and often close-welded.

2. *Suctive.*—Forced quickly into a crack otherwise opened, by fault or earthquake relieving strain, aided by gravitative suction, owing to the condensation by cooling of the gases from the magma; contacts generally fairly straight and not close-welded.

Nearly parallel is a classification according to the hot or cold condition of the country rock as follows:

1. *Secundine* (Latin *secundine*=afterbirth).—Injected into a hot country rock; contact generally irregular, close-welded, the grain generally equal throughout, either finer or coarser at or near the margin.

A characteristic mode of occurrence of lamprophyres, aplites and pegmatites.

2. *Subsequent.*—Injected into a cold country rock, with fine-grained selvages (the zones of increasing grain amounting to from one-quarter to one-tenth of the breadth of the dike) with straight and not close-welded contacts.

A characteristic occurrence of dikes not closely connected with larger masses or volcanic centers, and in composition close to Bunsen's normal basaltic magma or more basic.

The anchieutectic rocks which we are discussing are generally invasive secundine, but in case of shrinkage cracks, due to loss of heat or contact metamorphism, may be suctive and secundine too.

[2] *Jour. Geol.*, (1904), p. 91. See also *Wet and Dry Differentiation*, "Tufts College Studies," Vol. III, Pt. I.

stony margin (An. 2) in its less silica, more lime and magnesia is not so far on the toboggan slide toward the goal of "wet differentiation"—the magma from whence crystallizes pegmatite veins, and not so near to a granite (An. 4) as the glassy center (An. 1). We seem thus to have caught two stages in a differentiation which carried on on a large scale would lead to the hornblende granites described by Dresser.

As to the syntexis upon which Daly lays stress, there is no doubt that the inclusion and absorption of fragments of sandstone, *especially if they contained water in the interstices*, should promote the formation of micropegmatite, and zones of micropegmatite around such fragments in process of absorption are found in the Medford diabase, as Jaggar and others have seen. Possibly the water is quite as important as the silica. Very likely much of the red rock of Pigeon Point is of this nature. But the association of micropegmatite with diabases is too widespread for me to agree with Daly[1] that most granites are differentiates of syntectics. It is well worth considering how many are, like that described by Dresser, direct differentiates with the help of juvenile juices or mineralizers.

Oxides	1	2	3	4
	Glassy Central Leidleite	Stony Marginal Leidleite	Diabase Cobalt	Granite from Cobalt
SiO_2	61.69	59.21	50.12	72.33
TiO_2	1.00	1.06	.55	.74
Al_2O_3	14.43	14.06	15.70	12.99
Fe_2O_3	1.23	2.66	1.42	none
FeO	5.86	4.87	6.89	2.50
MnO	0.30	0.24	.....	.....
CaO	4.97	5.95	11.30	1.73
MgO	2.81	3.71	9.50	0.97
Na_2O	3.20	2.06	2.91	7.60
K_2O	1.72	2.83	1.07	.....
BaO	0.04	0.03	none	.....
H_2O at 105° C.	0.25	2.05	1.03	1.09
H_2O above 105° C	2.36	1.54	0.21	.....
Total	100.12*	100.47 †	100.84 ‡	100.95 §

* Including 0.02 Cl. 0.24 P_2O_5 † Including 0.2 P_2O_5.

‡ Bowen in *Can. Mining Inst.*, Vol. XII (1909), p. 523, diabase, including 14 S.

§ *Ibid.*, granite cutting diabase, including 1.00 CO_2.

[1] *Op. cit.*, p. 312, etc.

ON THE REPRESENTATION OF IGNEOUS ROCKS IN TRIANGULAR DIAGRAMS

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University of Chicago

It has been customary to represent three components in a triangular diagram by a dot, or four components by a triangle within the triangle. The writer, by means of only a dot and a line, plots without the use of a slide rule or any calculation whatsoever, the actual percentages of quartz, orthoclase, plagioclase, and dark minerals as well as the relative percentages of quartz, orthoclase, and plagioclase among the light constituents.

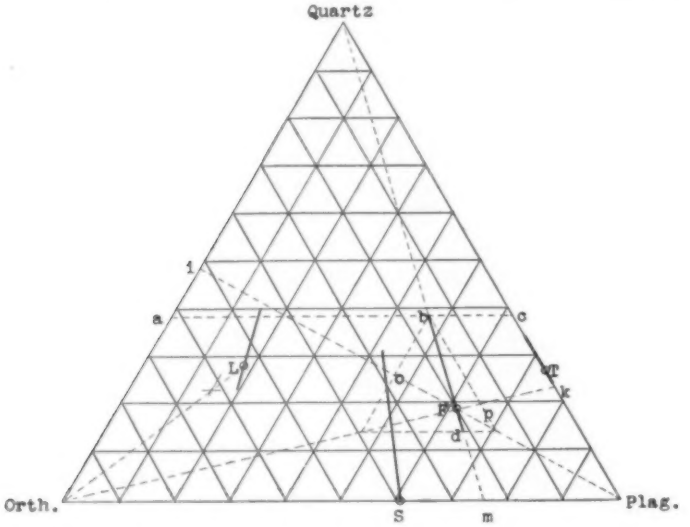
Let it be required to plot a rock with the following mode:[1]

Quartz	14 =	18.7
Orthoclase	15 =	20.0
Plagioclase	46 =	61.3
	75	100.0
Dark minerals	25	
	100	

The usual method is to reduce to 100, by means of a slide rule, the sum of the percentages of the minerals represented in the three corners of the diagram, and plot the point so obtained. The writer's method is shown in the figure. Draw three lines, parallel to the sides of the triangle, through the points representing the amounts of the corner minerals in the rock, in this case a horizontal line through 14 for quartz, a line sloping northeast and southwest through 46 for plagioclase, and a line sloping northwest southeast through 15 for orthoclase. Lay the side of a straight-edge on the apices of the two triangles and draw a short line (*bd*) through the small triangle from its apex to its base. Connect either of the

[1] The same method may be used in other ways to show the relative percentages of three components whose sum is not a hundred.

lower corners of the large triangle with the similar corner of the small one, and indicate its intersection with the line first drawn by a dot, *F*. The line *bd* and the spot *F* represent the rock. The point *F* is the same as that which would have been obtained by the slide rule, and gives the relative proportions of the light constituents (quartz [*mF*], orthoclase [*kF*], and plagioclase [*iF*]), in



the rock by its distances from the sides of the triangle opposite these names at the corners. The actual percentages of the minerals in the rock are also represented: *bc* or *pk* for orthoclase, *ab* or *io* for plagioclase, *bd* for the dark constituents, *dm* for quartz.

In a similar manner the composition of the rock at *L* may be read directly from the diagram, giving the values:

Quartz	23 =	27.7
Orthoclase	45 =	54.2
Plagioclase	15 =	18.1
	83	100.0
Dark minerals	17	
	100	

The rock at *S* is seen to consist of orthoclase 27 per cent, plagioclase 42 per cent, quartz 0 per cent, and dark minerals 31 per cent. The relative ratios of the light constituents are: orthoclase 39.1 per cent, plagioclase 60.9 per cent, and quartz 0 per cent. The rock at *T* consists of orthoclase 0 per cent, plagioclase 66 per cent, quartz 24 per cent, dark constituents 10 per cent. Relative ratios of the light minerals, plagioclase 73.5 per cent, quartz 26.5 per cent, and orthoclase 0 per cent.

The actual plotting takes much less time than the telling. In fact the small triangle is never plotted. The upper end (*b*) of the line is located at the dividing point between orthoclase (*bc*) and plagioclase (*ab*) on the horizontal line whose length (*ac*) is equal to the sum of the feldspars, and through this point the inclined line is drawn to the percentage position of quartz (*d*). One of the lower corners of the small triangle is located, without drawing it, and the intersection of the inclined line with the ferromagnesian mineral line used to determine the locus of the rock.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Adams, Sidney F. "A Microscopic Study of Vein Quartz," *Econ. Geol.*, XV (1920), 623–64. 48 figs. on 8 pls.

This study of the microscopic characteristics of vein quartz is confined to quartz of hydrothermal origin; magmatic, metamorphic, and replacement quartz are not included. A well illustrated and instructive paper.

Allen, E. T., and Lombard, Robert H. "A Method for the Determination of Dissociation Pressures of Sulphides, and Its Application to Covellite and Pyrite," *Amer. Jour. Sci.*, XLIII (1917), 175–95.

A secondary enrichment investigation of the Geophysical Laboratory, in which methods and apparatus are described.

Andersen, Olaf. "On Aventurine Feldspar," *Amer. Jour. Sci.*, XL (1915), 351–99. Figs. 13, pls. 3.

The schiller in certain feldspars was determined as being due to oriented, lamellar inclusions of hematite of various shapes and sizes. They originated through the unmixing of an originally homogeneous feldspar which contained iron oxides in solid solution. The lamellae were found always to be oriented after simple crystal forms.

Backlund, Helge. "Petrogenetische Studien an Taimyrgesteinen," *Geol. Fören. i Stockh. Förhandl.*, XL (1918), 101–203. Figs. 11, map 1.

This is a petrological study based upon about 500 specimens collected by the unfortunate Baron v. Toll in his expedition to Taimyr Peninsula, in northern Asia. The region is made up of gneisses, mica, and other schists, contact hornfeld-like rocks, and three types of granite. Many of the rocks were analyzed, and they are computed into norms and into the Osann system, while under granite the percentage modes

also are given. Besides detailed descriptions of the various rocks, there is a good discussion of movement in solidified rock, illustrated by numerous diagrams.

BARRELL, JOSEPH. "Relations of Subjacent Igneous Invasion to Regional Metamorphism," *Amer. Jour. Sci.*, I (1921), 1–19, 174–86, 255–67.

This paper, written by the late Professor Barrell in 1913 or 1914, has been edited and seen through the press by Frank F. Grout, and no better abstract of it can be given than Mr. Grout's own summary.

Evidence is presented that batholithic invasions widen downward and may occur close below many rocks where they have not been suspected. Batholiths like those in the American Cordillera seem to come to place without crustal compression, but those of the Archean shield and those of the later Appalachian invasions are accompanied by compression. A detailed study of three or four regions shows the metamorphism to be related to the igneous invasion more than to the depth and pressure. One of the regions of deepest burial and close folding in Pennsylvania shows slight metamorphism.

The action of magmas, both by heating and metasomatism, is reviewed. The solutions are not meteoric in origin. The results in minerals depend on equilibria—largely on the presence of H_2O and CO_2. The depth of anamorphism may be small, due (1) to weakness of some rocks, (2) to invasion of batholiths. An argument for shallow depth is based on the completeness of Archean metamorphism and the salt of the ocean as a measure of erosian.

The features of metamorphic rocks are reviewed and interpreted as due to one or another factor. Major factors are batholithic invasion and compression. Movements of solutions, selective crystallization, lit-par-lit injection gneisses, and the alternation of injection and mashing, each leaves its marks.

BARTRUM, J. A. "The Conglomerate at Albany, Lucas Creek, Waitemata Harbour," *Trans. New Zealand Institute*, LII (1920), 422–30. Pls. 2.

The conglomerates of the Albany Riverhead district (probably of Upper Miocene age) contain pebbles of greywacke, argillite, granodiorite, quartz-diorite, diorite-gneiss, diorite, anorthosite, dolerite, andesite, trachyte, and rhyolite. In this paper the igneous rocks are briefly described and four photomicrographs are given. It is suggested that the gneissic rocks in conglomerates, here and elsewhere in the North Island, perhaps furnish evidence of a terrain injected by batholitic intrusions, subjected to compressional stresses, and eroded before the deposition of the main mid-Mesozoic sedimentaries.

BARTRUM, J. A. "Additional Facts Concerning the Distribution of Igneous Rocks in New Zealand," *Trans. New Zealand Institute*, XLIX (1916), 418–24. Figs. 3.

Brief descriptions are given of hypersthene-basalt, troctolite, granodiorite with epidote (which the writer, not the reviewer, thinks primary), basalt with biotite (character of the feldspar of the rock not given), hornblende-basalt, andesite, diorite, and trachyte. Most of the descriptions are too brief and incomplete to permit passing judgment on the names.

BARTRUM J. A., "Additional Facts Concerning the Distribution of Igneous Rocks in New Zealand: No. 2," *Trans. New Zealand Institute*, LII (1920), 416–22. Figs. 5.

Here are brief descriptions of norite, dolerite, basalt, and hypersthene-andesite, and one more extended of quartz-norite. The dolerite is apparently the diabase of United States usage. The quartz-norite is described as "a moderately typical norite but for two considerations: first the plagioclase . . . . is somewhat acid, being in the main andesine-labradorite; secondly, there is . . . . a little interstitial quartz." A third objection which might have been given is the fact that besides hypersthene there is abundant augite, biotite, some hornblende, and "probably a third pyroxene." With a feldspar more acid than $Ab_{50}An_{50}$ why not call the rock quartz-hypersthene-diorite? The "third pyroxene" is described in considerable detail. All but one of its properties, including orientation, agree with hypersthene, the exception being the "extinction angle which was found to be from very small to 42°." *May* this mineral not be hypersthene? The reviewer has found that this mineral, in many cases, gives apparently inclined extinction in sections which are cut at right angles to the principal sections and yet show only one set of prismatic cleavage lines brought out by the grinding. Measuring then from the cleavage lines, the extinction is inclined, but it will usually be seen, if the stage is turned an equal number of degrees beyond the point of extinction, that there are here traces of the other cleavage. Random sections cutting all three axes in orthorhombic crystals do, of course, show inclined extinctions when measured from cleavage lines. Zoisite is mentioned as a mineral originally identified as apatite, and surprise is expressed that apatite does not occur although the analysis gives considerable P_2O_5. The sketch given of this

mineral may well represent a corroded apatite of a form not uncommon, and its occurrence surrounded by magnetite is indicative of the same mineral. Unless the fragments were large enough to permit of absolute determination as zoisite, the reviewer is inclined to think the original identification correct.

BECKE, F. *Ueber den Monzonit.* Festschrift C. Doelter. Dresden and Leipzig, 1920, 1–14. Fig. 1.

Monzonite, originally a collective name for all the different rocks found on Predazzo and Monzoni, has been variously used. Becke gives the following definition: Monzonite is a plutonic rock of granular texture. Its essential constituents, in the order of their crystallization, are magnetite, augite, hornblende, biotite, plagioclase (average composition andesine), and perthitic orthoclase. Small amounts of quartz or aegirite-augite or nephelite may occur. Accessory minerals are apatite and titanite. The dark and light constitutents, also the orthoclase and plagioclase, are of approximately equal amounts. Chemically the An: Ab: Or ratios are about 20:45:35; and the Ca:Mg:Fe=30:30:40. SiO_2 fluctuates around the point of saturation, so that quartz or a feldspathoid may occur in small amounts. Becke objects to the use of the term monzonite as applied to rocks of the "Pacific type." The silica content must be below 63–64 per cent. The term thus used is dependent upon the chemical composition. Used in the foregoing sense, many rocks described as quartz-monzonites are not such at all.

BENSON, W. N. "Report on the Petrology of the Dolerites Collected by the British Antarctic Expedition, 1907–1909," *Geology*, Vol. II, of Shackleton's Report. London, n.d., 153–60. Figs. 6.

Dolerites, in this report, are rocks composed essentially of basic plagioclase and pyroxene, with varying amounts of quartz. Following British usage they are called dolerites (diabases, United States). Since the name was originally given by Hauy to coarse-grained basalts, the use of the expression aphanitic dolerite seems anomalous. Several analyses, recast in the C.I.P.W. system, are given, and the rocks and component minerals are described in detail.

BENSON, W. N. "The Origin of Serpentine, a Historical and Comparative Study," *Amer. Jour. Sci.*, XLVI (1918), 693–731.

The author agrees with the general opinion that chrysotile- or antigorite-serpentine of large ultrabasic masses is derived from the alteration of originally intrusive peridotite; the hydration, in some cases at least, having been brought about by the agency of waters emanating from the same magma as that which produced the peridotite. Whether a peridotite which escaped hydration during the igneous epoch can subsequently be changed to serpentine by the action of deep circulating epigene waters is regarded as less clear though thought not improbable. The reviewer is glad to see followed here his own mode of indicating by asterisks, in the bibliography, works not seen by the writer.

BENSON, W. N. "The Geology and Petrology of the Great Serpentine Belt of New South Wales," Parts VI (Appendix) and VII. *Proc. Linnean Soc. New South Wales*, XLII (1918), 693–700, XLIII (1918), 320–94. Map 1, pls. 10, figs. 5.

The preceding papers of this series were reviewed in *Jour. Geol.*, XXV (1917), 493–95. In the present papers the rocks of the Attunga and Loomberah districts, and of a portion of the Goonoo Goonoo Estate are described. Two analyses of dolerites are given and keratophyres, dolerites, albite-dolerites, and granophyres are described rather completely, although much-to-be-desired model percentages are not given.

BEREK, M. and JENTZSCH, F. "Ein kleiner lichtstarker Monochromator, besonders für mikroskopische Beobachtungen," *Zeitschr. f. Instrumentenkunde*, 1914, 47–51. Figs. 2.

Describes a small monochromator for the production of monochromatic light. The instrument is only half as large as a petrographic microscope, and is so arranged that the whole spectrum may be made to pass through the opening without adjusting the light source or the microscope. The visible portion of the spectrum is normally 12 mm. but the emergence slit may be adjusted to any width. The emerging ray may be made parallel, convergent, or divergent by means of a lens in a sliding tube.

REVIEWS

Life of James Hall, Geologist and Paleontologist, 1811–1898. By J. M. CLARKE. Published by S. C. Bishop, Albany, N.Y., 1921. 8vo, pp. 565, pls. 14. Price $3.70 postpaid.

In this handsome volume of 565 pages, the deft pen of Dr. Clarke has set forth the life and times of James Hall in a most illuminating and fascinating way. While the story holds with tenacity and strict fidelity to the realities of Hall's remarkable career, the handling of its varied incidents is none the less most skilful, and the book is worthy of being read as a work of art. All the way through it bears evidence of unsparing labor in searching out from voluminous correspondence and tedious official records the essential details that give precision and life to the sketch. It is written from a deeply sympathetic and appreciative point of view, but the angularities and irascibilities of a strong and intensely earnest man are given their due place in the portraiture. These are touched with wonderful skill, so that they seem merely incidental shadows artistically designed to set off the high lights of the picture.

The book, however, is far more than a biographical sketch; it carries the reader into the very heart of investigative work as it was in those early times, while incidentally not a little light is thrown on the status of the allied sciences of the day. It gives most interesting glimpses of the leading scientific men of the time, including many of the foremost men in other than the geological sciences. Dr. Hall had a wide acquaintance with these, and the abundant extracts from his intimate correspondence with them shed suggestive side lights on the personal aspects of pioneer investigation and the troubles, political and otherwise, which attended it. We doubt if there is any other text that carries the reader so close home to the inner history of our own and allied sciences in this country during the early and middle stages of the last century. No student of geological and paleontological progress should miss the opportunity to read this thesaurus of information on a most vital stage of early American science.

T. C. C.

The Geology of Northeastern Rajputana and Adjacent Districts. By A. M. HERON, B.Sc., F.G.S., Assoc. Inst. C.E., Assistant Superintendent Geological Survey of India. Calcutta: Memoirs of the Geological Survey of India, Vol. XLV, Part I, 1917. Pp. 128, pls. 26.

This report gives the results of a general geological survey of the region started in 1908, made with special reference to stratigraphy. The formations present include only the pre-Cambrian overlain by unconsolidated post-Tertiary beds. The chief physiographic feature is that of an ancient, folded, mountain complex, in the last stages of denudation, surrounded by gently sloping plains. There is a general discussion of local correlations and nomenclature.

There is no mineral wealth of any great importance. Quartzite is quarried rather extensively, but chiefly for local use. The report is accompanied by a geologic map and a number of structure sections.

A. C. McF.

The Phosphate Deposits of South Australia. By R. LOCKHART JACK, B.E., F.G.S. Adelaide: Geological Survey of South Australia, Bulletin No. 7, 1919. Pp. 135.

The author considers briefly the mode of occurrence, sources, method of working, and the preparation of the rock phosphate. Both guana deposits and rock phosphate are worked. The latter is associated with sedimentary rocks of Cambrian or even possibly pre-Cambrian age which are usually highly metamorphosed. It is almost invariably found in close association with the limestones and marbles or the adjoining argillaceous rocks. Whether the phosphate is primary or secondary is not known. Brecciation of the associated rock is conspicuous even at considerable depth.

A. C. McF.

Systematic Report on the Cambrian and Ordovician of Maryland. By R. S. BASSLER. Maryland Geological Survey, 1919.

In a review of this report in the last issue of this *Journal*, it was stated that the proposed Ozarkian and Canadian systems "are not recognized" instead of "are recognized." It is the desire of the reviewer to call attention to this correction. The two systems are not only recognized but are discussed in some detail, the Conococheague limestone being referred probably to the former, and the Beekmantown limestone to the latter.

A. C. McF.

ERRATA

Journal of Geology, Volume XXX, on page 164, line 2 from the bottom, and page 165, line 2 from the top, read Radley, instead of "Bailey."